

Review Article

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From Fame to Polyol Esters: Can Palm Oil Derived Biodegradable Drilling Fluids Meet the HTHP Deepwater Performance Window? A Critical Review

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ABSTRACT

Environmental constraints on conventional oil-based drilling fluids and increasingly severe downhole conditions have intensified the search for biodegradable synthetic-base fluids with both ecological and high-performance characteristics. Palm-derived esters are attractive because an established oleochemical platform can produce fatty-acid methyl esters (FAME), branched monoesters, and higher polyol esters with markedly different molecular and physicochemical properties. This qualitative literature review critically evaluates whether these materials can progress from promising laboratory fluids and lubricants to reliable components of high-temperature/high-pressure (HTHP) and deepwater drilling systems. Evidence is synthesized through a structure property performance readiness framework encompassing rheology, lubricity, filtration, emulsion stability, hydrolysis, thermal and oxidative degradation, contamination tolerance, elastomer compatibility, foaming, biodegradability, environmental fate, economics, and field readiness. The evidence indicates that palm FAME offers favorable lubricity, biodegradability and relatively low viscosity but remains vulnerable to alkaline hydrolysis, saponification, oxidation and formulation-dependent instability. Branched PFAD-derived esters provide an important intermediate pathway, while neopentyl polyol and emerging estolide esters potentially provide superior viscosity-temperature behavior, flash point and thermal stability. Nevertheless, direct palm-specific evidence under combined deepwater low-temperature/high-pressure and severe HTHP conditions remains limited. Palm esters should consequently be viewed as a molecular design platform rather than a drop-in commodity replacement. A staged qualification roadmap is proposed to move promising formulations from molecular screening through dynamic pressurized testing to offshore field validation.

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Introduction

Drilling fluids operate simultaneously as hydraulic, mechanical, chemical, and thermal-control systems. They transport cuttings, maintain hydrostatic pressure, suspend weighting material during static periods, lubricate the drill string, reduce filtration into permeable formations, stabilize exposed rock, and facilitate transmission of hydraulic energy to the bit. These requirements become substantially more difficult in deep, extended-reach, high temperature/high-pressure, and offshore deepwater wells, where fluid properties may change strongly with temperature, pressure, solids loading, and chemical contamination. Modern reviews consequently treat rheological stability, filtration control, lubricity, salt tolerance, and environmental acceptability as mutually dependent design criteria rather than independent fluid properties [1-4]. A recent bibliometric synthesis likewise shows that drilling-fluid research is moving toward multifunctional and chemically tailored formulations rather than optimizing individual mud properties in isolation [5].

Oil-based and synthetic-based invert-emulsion fluids remain attractive in technically challenging wells because they provide strong shale inhibition, lubricity, temperature tolerance and wellbore stability. Their disadvantages include environmental persistence, cuttings-treatment requirements, waste-management

costs and potential ecological impacts. These constraints have stimulated extensive work on biodegradable additives, vegetable-oil derivatives, synthetic esters, biodiesel, environmentally benign polymers and nanomaterial-assisted systems [6-9]. Environmental performance, however, cannot be inferred solely from the renewable origin of one component. Toxicity and biodegradability may change after high-temperature/high-pressure exposure, while the complete mud contains emulsifiers, alkalinity agents, brines, weighting solids and other additives that influence its environmental profile [10].

Palm oleochemicals are particularly interesting because palm oil and its refining streams can be transformed into a continuum of chemically distinct esters. At the simplest level, transesterification yields palm fatty-acid methyl ester, or palm FAME. Subsequent or alternative esterification routes can produce branched monoesters such as 2-ethylhexyl esters and more complex neopentyl polyol esters based on neopentyl glycol (NPG), trimethylolpropane (TMP) or pentaerythritol (PE). More recently, palm fatty acid distillate (PFAD), a refinery side stream containing a high concentration of free fatty acids, has been investigated as a raw material for polyol and estolide base stocks. These molecules differ in molecular mass, branching, polarity, viscosity, crystallization behavior, volatility, oxidation resistance and hydrolytic response; therefore, “palm-based drilling fluid” should not be treated as a chemically homogeneous category [11-15].

Two early drilling studies established the intellectual basis for this field. Kania et al. showed that palm-derived polyol esters

could provide substantial lubrication in bentonite drilling-fluid suspensions, although some ester structures also altered gel characteristics or promoted foaming [16]. Said and El-Sayed subsequently demonstrated that palm FAME could act as the continuous base fluid of a high-performance flat-rheology drilling fluid [17]. These studies were important proofs of concept, but they preceded the recent rapid expansion of HTHP, deepwater, ester-fluid and sustainable-biotribology research.

The evidence base has since evolved. A 2025 study directly evaluated a 2-ethylhexyl ester produced from PFAD as an ester-based drilling-fluid base oil. A formulation containing 60% of this PFAD-derived ester and 40% commercial ester showed favorable electrical stability and filtration behavior relative to selected conventional oil-based reference fluids, including HTHP filtration tests at temperatures up to 100 °C [18]. This finding is a significant step beyond generic extrapolation from biodiesel, yet a 100 °C filtration test cannot by itself establish suitability for severe HTHP wells operating at much higher bottomhole temperatures, nor does it reproduce the cold-riser/high-pressure segment of an offshore deepwater circulation loop.

The central research gap therefore concerns translation. Palm esters have shown biodegradability, lubricity and encouraging drilling-fluid performance, but there is insufficient integration of hydrolysis, thermal degradation, low-temperature rheology, HTHP filtration, emulsion stability, contamination tolerance, elastomer compatibility, foaming, environmental fate and field reliability. Comparable biodiesel-based drilling-fluid literature repeatedly identifies excessive viscosity, poor low-temperature properties, emulsion instability and hydrolytic sensitivity as continuing technical problems, although branching, molecular redesign, blending and nanomaterial stabilization provide possible remedies [19,20].

This review consequently asks whether palm-derived esters can meet the complete HTHP deepwater performance window, rather than whether they can pass isolated laboratory tests. It evaluates palm FAME, branched PFAD-derived esters and palm polyol esters through a Structure-Property Performance Readiness framework and uses evidence from palm-specific studies, other ester drilling fluids, deepwater rheology, HTHP drilling systems and contemporary biolubricant research.

Literature Review and Conceptual Foundations

Drilling Fluids as Integrated Systems

A drilling fluid cannot be evaluated from base-oil properties alone. In an invert-emulsion system, the continuous oil or synthetic phase interacts with an internal aqueous brine phase, primary and secondary emulsifiers, lime, organophilic clay or alternative rheological modifiers, fluid-loss additives and weighting materials. Performance emerges from interactions among these components. Electrical stability, for example, reflects the integrity of the water-in-oil emulsion rather than a single base-oil property, while barite sag depends on low-shear rheology, density, temperature, particle interactions and static aging.

This systems perspective explains why apparently attractive renewable base stocks sometimes produce disappointing mud formulations. Fadairo et al. demonstrated that neem biodiesel could function as the continuous phase of an invert-emulsion mud and provide promising rheology, lubricity and flash-point performance [21]. Jiang et al. developed a biodiesel-based flat-rheology drilling fluid with strong temperature and contamination

performance, yet hydrolysis and saponification required deliberate control through formulation chemistry [22]. Reviews of biodiesel fluids similarly emphasize that molecular modification and blending may be required before a biodiesel becomes a reliable drilling-fluid base stock.

Water-based drilling-fluid research provides equally important lessons because many potential palm-derived esters may ultimately be deployed as lubricating additives rather than the continuous phase. Environmentally benign polymers, biogenic nanoparticles, natural inhibitors and waste-derived additives have demonstrated that environmentally preferable components can be incorporated without sacrificing all performance requirements, although high-temperature and contamination stability remain decisive constraints [23–28].

HTHP is a Multidimensional Rather Than Purely Thermal Challenge

High-temperature/high-pressure drilling conditions alter viscosity, polymer conformation, emulsion structure, fluid-loss behavior and solids suspension. A useful fluid must avoid excessive thermal thinning while also resisting irreversible degradation and high-temperature thickening. The problem becomes more demanding at high mud density because weighting solids create additional sag and rheological challenges. Mao et al. emphasized the need for conceptual control of rheological behavior at ultra-high temperature and pressure, while Gautam et al. demonstrated from a broad comparison of HTHP systems that structure property relationships of additives strongly affect temperature resistance, filtration, salt tolerance and lubricity [29].

Recent high-performance systems demonstrate the severity of the benchmark that biodegradable ester fluids would need to meet. Huang et al. reported a high-density saturated-brine polymeric system capable of functioning at approximately 200 °C, while Wagle et al. addressed the design of invert-emulsion fluids for high-temperature/high-pressure conditions and highlighted the continuing importance of robust rheology and sag resistance; He et al. also demonstrated how amphiphilic multiblock polymers can strengthen high-temperature oil-based-fluid gel structure [30–32]. High-temperature drilling-fluid lubricants are likewise expected to preserve adsorption and load-bearing films despite salinity, temperature, and high contact stress [33,34]. Recent nanocomposite-viscosifier research has also demonstrated low filtration under high-salinity conditions at temperatures as high as 220 °C, further illustrating the demanding performance benchmark that renewable ester systems must eventually match [35]. A palm ester intended for severe HTHP service must therefore be judged against mature high-temperature formulations rather than against room-temperature vegetable-oil benchmarks.

Deepwater Drilling Creates the Opposite Temperature Challenge

Deepwater wells expose circulating fluid to very low temperatures near the seafloor while simultaneously requiring it to tolerate much higher temperatures at depth. This temperature excursion makes rheological flatness especially important. Excessive viscosity at low temperature increases pump pressure and Equivalent Circulating Density (ECD), potentially narrowing the margin between pore and fracture pressures. Conversely, excessive thinning at bottomhole temperature can reduce hole-cleaning and suspension capacity.

Experimental and review studies consistently identify temperature- and pressure-dependent rheology as central deepwater problems. Maiti et al. demonstrated strong low-temperature/high-pressure effects on water-based drilling-fluid behavior, while Yang et al. reviewed the continuing challenge of low-temperature rheology in high-performance ocean deepwater drilling fluids [36,37]. Temperature-sensitive rheology modifiers have consequently been developed to counteract cold thickening and provide more uniform behavior across the circulation loop [38-40].

For ester-based fluids, this is particularly relevant because molecular structure affects both viscosity and crystallization. The ideal HTHP deepwater palm-derived ester cannot merely possess a high flash point and adequate hot-fluid viscosity; it must also avoid excessive low-temperature viscosity and crystallization in the riser. This creates an optimization problem in which increased molecular mass and intermolecular interaction may improve thermal robustness but simultaneously make cold-flow behavior more difficult.

From Triglyceride to Engineered Ester

Vegetable oils possess excellent intrinsic lubricity because their polar ester groups adsorb effectively at metal surfaces, but unmodified triglycerides frequently suffer from oxidative instability and unfavorable low-temperature behavior. Chemical modification through transesterification, branching, epoxidation, esterification with polyols and related approaches is therefore central to modern biolubricant development [41-45].

FAME removes the glycerol backbone and produces smaller ester molecules. This generally reduces viscosity relative to the parent triglyceride and can improve fluidity, but the ester remains susceptible to hydrolysis and its oxidation behavior continues to depend strongly on fatty-acid unsaturation. Branched alcohol esters such as 2-ethylhexyl esters introduce steric disruption that inhibits orderly packing and can improve cold-flow properties. Polyol esters based on NPG, TMP, and PE possess larger branched structures and can deliver high viscosity indices, low volatility, and improved thermal behavior, making them important synthetic-lubricant base stocks. Recent work on β -hydrogen-free polyol architectures reported viscosity indices of 189-222, thermal-onset temperatures of 258–285 °C, and melting points down to –47.6 °C, illustrating how molecular architecture can simultaneously influence thermal stability and cold-flow behavior [46].

Palm-specific research demonstrates substantial tunability within this latter class. Palm-oil-derived TMP esters have been produced enzymatically, palm-kernel-derived lubricant esters have been synthesized through multiple modification routes, and steric effects have been shown to influence the miscibility and properties of palm-derived pentaerythritol esters [47]. NPG-based palm esters have also demonstrated favorable lubrication properties. Reviews of plant-based TMP esters explicitly identify drilling fluids among possible applications of these high-performance biolubricants [48].

The most recent evidence extends the design space further. Suemanotham et al. converted PFAD into NPG, TMP and di-TMP polyol esters, showing that polyol structure strongly influenced esterification and lubricant characteristics. Hambali and Raof demonstrated a palm-derived NPG diester with high viscosity index and favorable tribological behavior, although the application investigated was electric-vehicle lubrication rather than drilling. Pitakjakkpipop et al. produced PFAD-derived estolide esters with improved low-temperature and lubricant properties [49,50]. These studies should not be presented as drilling-fluid validation, but

they provide a rational molecular-design toolbox for the next generation of palm-based drilling fluids.

Environmental Performance Requires More Than A “Biodegradable” Label

Ester fluids are attractive partly because ester bonds can facilitate biodegradation compared with many mineral and synthetic hydrocarbon fluids. Yet biodegradation depends on molecular weight, branching, temperature, oxygen availability, microbial population and environmental matrix. Folyan et al. experimentally evaluated aerobic and anaerobic degradation of a synthetic ester drilling fluid under marine deepwater conditions and demonstrated that environmental fate differs according to fluid chemistry and degradation conditions. Folyan et al. further compared new ester base fluids with synthetic hydrocarbon systems and found favorable aerobic biodegradation while also highlighting the relationship between carbon structure, viscosity and deepwater suitability [51,52].

Environmental qualification should therefore incorporate not only a standard biodegradation percentage but also the temperature and oxygen regime of the receiving environment. HTHP aging can alter the biodegradability and toxicity of drilling-fluid additives. Waste-management studies likewise emphasize that the environmental burden of drilling fluid includes contaminated solids, liquid waste, transport, treatment and disposal rather than simply the source of the base oil [53]. The relevant question is thus whether a palm-derived formulation reduces environmental burden over its operational life-cycle.

Method

This study adopts a qualitative literature review, explicitly rather than a systematic literature review. Its purpose is interpretive integration of heterogeneous evidence across petroleum engineering, tribology, oleochemistry, polymer science and environmental research. The method is appropriate because direct palm-specific drilling-fluid studies remain too few and experimentally heterogeneous for robust quantitative synthesis, while important evidence regarding underlying degradation and lubrication mechanisms occurs outside the drilling-fluid literature.

The principal evidence window was 2020–2026. Literature was considered from reputable peer-reviewed journals indexed by major academic databases and publisher platforms, including journals in petroleum engineering, chemical engineering, tribology, energy, environmental science and materials science. Two earlier palm-specific studies Kania et al. and Said and El-Sayed were retained as foundational exceptions because they directly established the drilling-fluid relevance of palm polyol esters and palm FAME, respectively.

Search concepts were organized into five thematic clusters. The first two clusters covered palm oil, PFAD, palm FAME, polyol esters, NPG esters, TMP esters, pentaerythritol esters, biodiesel, vegetable oils, and ester-based drilling fluids. The remaining clusters addressed HTHP drilling-fluid behavior, thermal stability, filtration, rheology and sag; deepwater low-temperature and high-pressure rheology and ECD; and biodegradation, ecotoxicity, lubricant performance, and ester degradation.

Evidence was coded through the Structure Property Performance Readiness framework. “Structure” included feedstock, chain length, saturation, alcohol moiety and branching. “Property” included density, viscosity, viscosity index, flash point, pour point, hydrolytic stability, oxidation stability and lubricity. “Performance”

covered mud rheology, filtration, emulsion stability, electrical stability, sag, foam and contamination tolerance. “Readiness” addressed realistic temperature-pressure cycling, dynamic circulation, elastomer compatibility, field trials, economics and environmental qualification.

Interpretation also used an evidence-strength hierarchy. Direct palm-specific drilling-fluid evidence was assigned greater translational weight than non-palm ester drilling-fluid evidence, which in turn was weighted more strongly than palm biolubricant studies conducted outside drilling. This distinction was necessary to prevent favorable tribological or thermal properties measured in another application from being presented as proof of downhole performance.

Results

Theme 1: Palm Ester Chemistry Defines the Performance Envelope
The literature indicates that there is no technically meaningful single category called a “palm ester drilling fluid.” FAME, branched monoesters, polyol esters and estolides are different molecular platforms. Palm FAME benefits from comparatively low molecular mass and viscosity and therefore represents an intuitive base-fluid candidate. The original palm-FAME flat-rheology study demonstrated that such a system could be formulated at drilling-relevant density and maintain promising performance after aging and contamination tests. Later biodiesel research confirms that

fatty-acid esters can achieve acceptable drilling-fluid rheology, lubricity and flash point, but also shows why their molecular structure matters.

Branched monoesters provide a particularly important intermediate pathway. Pauzi et al. [18] showed that 2EH-PFAD possessed physicochemical characteristics suitable for drilling-fluid use and that blending it with a commercial ester produced an invert-emulsion fluid with promising rheology, electrical stability and filtration control. Branching around the alcohol-derived portion of the molecule disrupts efficient molecular packing and therefore provides a logical route to better cold-flow characteristics than more symmetrical or readily crystallizing molecules.

Polyol esters move the design further from conventional biodiesel. NPG, TMP and PE provide compact branched alcohol centers from which multiple fatty-acid chains extend. Such structures have long been valued in synthetic lubrication because they can combine polarity and strong surface adsorption with improved viscosity-temperature performance and lower volatility. Palm-specific studies confirm that these properties can be engineered through polyol selection and ester composition. Figure 1 positions palm feedstock as the starting point of a molecular-design pathway rather than as the drilling-fluid product itself. It therefore emphasizes that the relevant engineering question concerns how ester architecture changes the usable HTHP deepwater operating window.

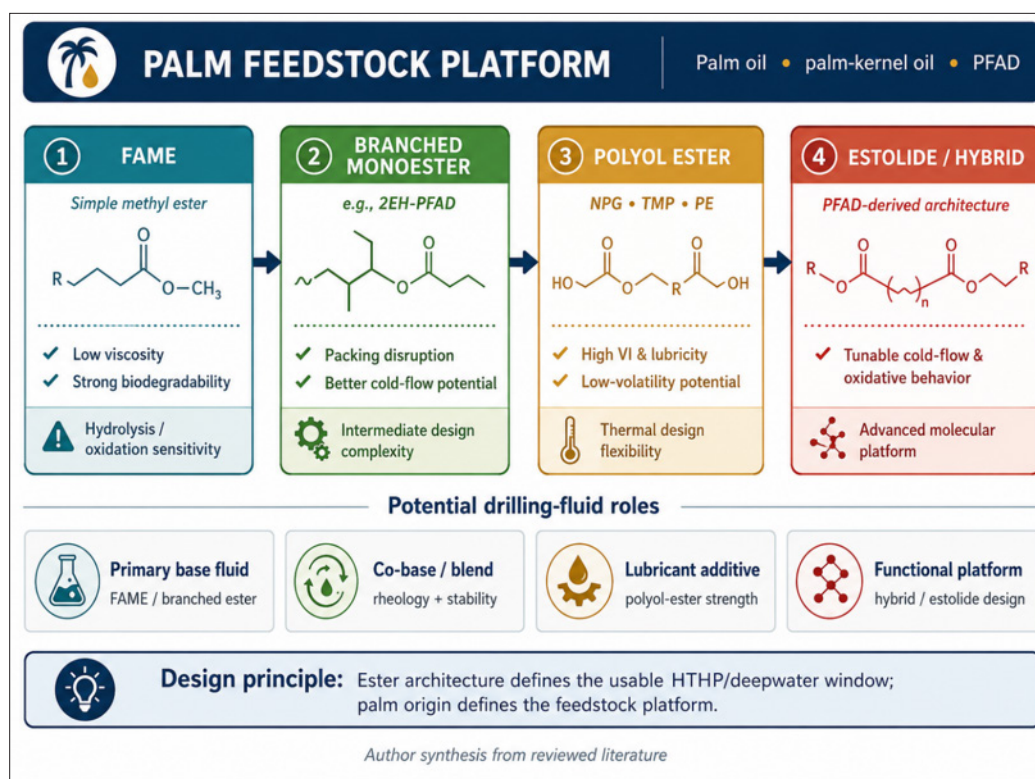


Figure 1: Molecular Pathways from Palm Feedstocks to Drilling Fluid Functions

Figure 1 illustrates why the research question cannot be reduced to asking whether palm oil “works” as a drilling fluid. The molecular transformation chosen after palm refining determines the relevant operating envelope. New PFAD studies are particularly significant because they potentially combine feedstock circularity with chemical architectures specifically designed to improve base-oil performance.

Theme 2: Lubricity is One of The Strongest Arguments for Ester Chemistry

Ester polarity promotes adsorption on metallic surfaces, while the hydrocarbon chains provide a low-shear interfacial layer. This combination underpins the strong boundary lubrication associated with vegetable-oil esters and polyol esters. Contemporary reviews consistently identify high lubricity and friction reduction among the principal advantages of vegetable-oil-based lubricants [54,55].

Drilling-fluid research confirms that this mechanism can translate into practical performance. Yang et al. and Zhao et al. identify vegetable oils, synthetic esters, polyols and related environmentally friendly molecules as important routes for reducing drilling torque and friction. Dai et al. combined methyl oleate and oleamide in a drilling lubricant and subsequently reported field application in which the additive reduced drag without destabilizing the weak-gel fluid [56-58]. Although this was not a palm-specific ester, it is important translational evidence that fatty-acid ester lubrication can survive beyond bench tribometers.

Palm-specific polyol esters provide complementary evidence. Kania et al. reported large reductions in friction when selected palm-derived polyol esters were incorporated into bentonite suspension. However, not all esters behaved identically; certain structures produced foaming or changed gel characteristics. This observation is critical. High lubricity is necessary but insufficient: the preferred molecule must reduce friction without disrupting rheology, introducing persistent foam or destabilizing other mud components.

Theme 3: The Relevant Target is Flat Rheology Over the Entire Circulation Loop

Deepwater drilling places contradictory demands on fluid rheology. At the mudline, low temperature can sharply increase base-fluid and emulsion viscosity. At the bottom of a deep well, high temperature may cause thinning, additive desorption, chemical degradation or emulsion deterioration. A deepwater ester fluid that performs extremely well at 25°C can therefore be operationally unsuitable.

Maiti et al. And Yang et al. demonstrate why rheological testing should encompass both low temperature and high pressure.

Temperature-sensitive polymer systems developed by Wang et al. illustrate contemporary attempts to counteract low-temperature thickening, while mechanistic analysis by Wang et al. reinforces that composition-dependent interactions control this behavior. These observations provide a benchmark for palm esters: viscosity should be characterized across the entire expected temperature-pressure trajectory, not at one or two conventional API temperatures.

Unsaturation can improve low-temperature flow because cis double bonds disrupt ordered packing, but it may simultaneously lower oxidative stability. Higher saturation generally improves oxidation resistance but can increase crystallization and pour point. Branching can partially decouple this trade-off by interfering with packing without necessarily requiring a highly polyunsaturated fatty-acid profile. This is one reason why branched PFAD monoesters, NPG/TMP esters and PFAD estolides deserve targeted drilling-fluid evaluation.

Folayan et al. showed that ester molecular structure significantly influenced critical deepwater base-fluid properties and biodegradability. Their comparison of caprylate- and linolenate-derived synthetic esters illustrates the central trade-off: chain length and unsaturation affect viscosity, cold-flow behavior and biodegradation simultaneously. Folayan et al. similarly emphasized relationships between feedstock fatty-acid structure and synthetic-base-oil drilling performance [59]. Figure 2 summarizes the chemistry–performance trade-offs as a multidimensional design map rather than as a simple ranking of FAME and polyol esters. This presentation makes the evidence gaps visible alongside the relative strengths of each ester class.

PROPERTY / EVIDENCE	FAME	Branched 2EH ester	Polyol ester
Low viscosity	High	High–moderate	Moderate
Low-temperature potential	Moderate–high	High	Structure-dependent
Lubricity	High	High	Very high
Flash point	Moderate–high	High	High–very high
Hydrolytic robustness	Lower	Potentially improved	Potentially higher*
Thermal / oxidative potential	Feedstock-dependent	Improved flexibility	High design potential
Biodegradability	Generally strong	Strong potential	Molecule-dependent
Formulation simplicity	Higher	Moderate	Lower
Direct palm drilling evidence	Foundational	Emerging	Very limited
HTHP field evidence	Insufficient	Insufficient	Insufficient

Interpretive key

● relative strength ● conditional / design-dependent ● limitation / evidence gap

* Depends on ester structure, formulation chemistry, water activity, alkalinity and aging conditions.

Qualitative author synthesis; not standardized test scores

Figure 2: Qualitative Structure Property Tradeoff Map

The figure shows why no ester class is universally superior. FAME may offer the lowest-viscosity and simplest route, whereas polyol esters offer greater molecular design freedom. The practical solution may therefore involve a mixture in which one ester serves as the low-viscosity continuous phase while a more robust polyol ester contributes lubricity or temperature resistance.

Theme 4: Hydrolysis and Saponification Remain Central Fame Failure Modes

The ester linkage that contributes to biodegradability also creates chemical vulnerability. Water and alkaline conditions can promote hydrolysis, while the presence of strong alkalinity or lime can encourage formation of fatty-acid salts. In invert-emulsion drilling systems, lime is routinely employed to maintain alkalinity and support emulsifier chemistry; consequently, the possibility of ester hydrolysis is operationally important rather than merely theoretical.

Aboulrous et al. identify hydrolytic instability as one of the principal limitations of biodiesel-based drilling fluids and note that structural modification, blending and formulation strategies may improve resistance. Jiang et al. demonstrated that control of composition and emulsion chemistry can mitigate hydrolysis-related thickening in a biodiesel flat-rheology system. These findings directly inform palm FAME because its fatty-acid methyl ester chemistry belongs to the same broad reaction class.

Hydrolysis can change far more than the base-oil composition. Formation of fatty acids or soaps changes polarity, interfacial behavior and emulsion structure. It may increase viscosity, alter wettability of weighting materials and solids, change calcium chemistry and destabilize electrical properties. Consequently, hydrolysis kinetics should be measured in the actual formulated mud over realistic aging periods, temperatures, lime concentrations and water activities.

The 2025 2EH-PFAD work is encouraging because branching and the use of a higher alcohol ester represent a molecular step away from conventional FAME, but its current performance data do not yet establish long-duration hydrolytic stability under aggressive HTHP alkalinity. This should become one of the highest priorities for follow-up research.

Theme 5: HTHP Performance Requires Resistance to Irreversible Chemical Change

Thermal stability should be distinguished from acceptable instantaneous viscosity at elevated temperature. A fluid may remain pumpable during a short test yet undergo oxidation, ester cleavage, additive decomposition or irreversible rheological change after prolonged aging. The HTHP literature demonstrates that advanced drilling fluids must maintain filtration, suspension and rheology after severe exposure.

Fatty-acid unsaturation is an important vulnerability because double bonds provide sites for oxidation. Oxidative products can polymerize or increase polarity and viscosity. Vegetable-oil biolubricant research therefore relies heavily on molecular modification and antioxidant strategies. Reviews by Uppar et al., Nogales-Delgado et al. and Hamnas and Unnikrishnan consistently identify oxidative and thermal stability as key barriers to replacing mineral lubricants with unmodified vegetable oils.

Polyol ester research suggests a promising route. Palm-derived TMP, PE and NPG esters can achieve favorable viscosity indices,

flash points and thermal properties. Suemanotham et al. reported particularly encouraging properties for PFAD-derived polyol esters, while Hambali and Raof found high viscosity index and favorable friction performance for a palm NPG diester. These results justify drilling-specific testing but do not eliminate the need for it.

High-temperature drilling-fluid lubricant studies provide the required performance benchmark. Wang et al. [33] developed an environmentally friendly borate-ester lubricant capable of functioning under combined high-temperature and high-salinity conditions, while Geng et al. demonstrated that advanced lubricant architectures can maintain useful behavior at very high temperature. More directly relevant to polyol-ester design, Pang et al. reported that a pentaerythritol-oleate/graphene lubricant retained strong tribological performance after aging at 240 °C, showing that ester-based boundary lubrication can remain functional at ultrahigh temperature when supported by a thermally robust solid-lubricant architecture [60]. A palm polyol ester proposed for HTHP use should therefore be compared against such engineered systems rather than simply against diesel or raw vegetable oil.

Theme 6: Filtration, Emulsion Stability and Sag Must Be Evaluated as Formulation-Level Outcomes

One of the strongest aspects of the 2025 PFAD study is that it moved beyond measuring only base-oil flash point, pour point and viscosity. Pauzi et al. formulated actual ester-based drilling fluids and evaluated parameters including fluid loss, mud-cake thickness, rheology and electrical stability. This is the type of translational testing needed throughout the palm-ester literature.

However, HTHP filtration to 100 °C is only an initial portion of the target envelope for genuinely severe HTHP applications. Subsequent work should extend static and dynamic aging to higher temperatures and pressures, use high-density formulations, and examine whether solids remain oil-wet and suspended after aging. Dynamic sag testing and viscoelastic low-shear characterization would be particularly important.

The wider literature demonstrates several pathways for strengthening environmentally acceptable formulations. Jiang et al. developed advanced water-based drilling and completion-fluid technology addressing wellbore quality and reservoir protection. Li et al. combined laponite nanoparticles with biodegradable derivatives, while Patidar et al. reviewed biodegradable nanoparticle-based additives [61,62]. These studies suggest that palm ester systems need not rely exclusively on conventional organoclay chemistry. Nano- or polymer-assisted stabilization may ultimately allow lower organoclay loadings and flatter rheology.

Theme 7: Contamination, Elastomers and Foaming Represent Major Evidence Gaps

Operational drilling fluids are continuously exposed to contaminants. Drill solids increase the dispersed-solid fraction; saltwater influx changes water-phase activity; cement introduces calcium and high alkalinity; formation fluids alter the oil/water balance; and prolonged circulation introduces fine solids and degradation products. A base ester that appears stable in a freshly mixed laboratory mud may respond very differently after contamination.

Current environmentally friendly drilling-fluid studies increasingly test salt, solids and thermal contamination because laboratory purity is an unrealistic benchmark. Examples range from biodegradable

additives and waste-derived materials to nanoparticles and high-salinity polymers [63,64]. Palm-ester development should adopt the same philosophy.

Elastomer compatibility is another neglected issue. Ester molecules can interact differently from hydrocarbons with seals, hoses and downhole elastomeric components, potentially causing swelling, extraction of plasticizers, hardening or changes in mechanical properties. Peixoto et al. in evaluating a synthetic carbonate drilling-fluid base, emphasized hydrolytic stability and compatibility characteristics relative to ester systems [65]. This comparison is useful because environmental preference alone does not compensate for seal failure or equipment incompatibility. Foaming deserves similar attention. The early palm polyol-ester drilling-fluid work observed that some structures generated foam or modified gel texture. Entrained gas can interfere with density measurement, pumping, solids control and surface handling. Foam tendency and foam persistence should therefore be treated as formal qualification parameters for palm polyol ester additives.

Theme 8: Biodegradability is a Strength, But Whole-Fluid Evidence is Necessary

Ester-based fluids have a credible environmental rationale. Folyan et al. found rapid aerobic degradation for selected ester synthetic fluids relative to paraffinic synthetic comparators, while their marine deepwater work demonstrated that both aerobic and anaerobic processes must be considered [51]. Green drilling-fluid reviews likewise emphasize biodegradable components as an important pathway toward reducing drilling waste impacts.

Nevertheless, “biodegradable base oil” should not be treated as synonymous with “environmentally benign drilling fluid.” The complete formulation contains numerous chemicals, and HTHP exposure may generate degradation products whose environmental behavior differs from that of the starting materials. Deng et al. showed that high temperature and high pressure can influence biodegradability and biotoxicity of drilling-fluid additives. Environmental assessment should therefore compare fresh and aged muds.

The most informative qualification program would combine ready/inherent biodegradation tests with marine aerobic and anaerobic experiments, acute and chronic ecotoxicity testing, sediment exposure, and chemical characterization of HTHP-aged products. Such analysis would permit a more defensible comparison with mineral oil, GTL, paraffin, LAO and existing ester synthetic fluids.

Theme 9: PFAD May Improve the Circular-Economy Proposition
Use of edible-grade palm oil for drilling-fluid production invites an obvious allocation question because the same feedstock serves food, oleochemical, energy and other markets. PFAD changes this narrative by using a refinery side stream rich in free fatty acids. Recent work demonstrates that PFAD can be transformed into drilling-fluid monoesters, polyol esters and estolide base stocks.

This does not make PFAD economically free. Esterification requires alcohols, catalysts, energy, purification and product-quality control. Highly engineered polyol esters may cost more than commodity FAME. Filon et al. and Nogales-Delgado et al. show more broadly that multi-stage ester synthesis can produce higher-performance renewable lubricants but adds process complexity [66]. The appropriate economic comparison must therefore include not only base-oil purchase price but additive requirements, dilution, drilling efficiency, waste treatment, transport, cuttings disposal and environmental compliance.

Feedstock traceability should also form part of sustainability evaluation. Renewable chemistry cannot automatically substitute for responsible feedstock production. PFAD utilization is particularly attractive where it creates additional value from an existing refining stream without requiring dedicated expansion of primary oil production.

Theme 10: Laboratory Evidence Has Not Yet Closed the Field-Readiness Gap

The current evidence indicates that palm-derived ester drilling fluids are technologically plausible but not yet broadly qualified for severe HTHP deepwater service. The evidence hierarchy is uneven. Palm FAME has foundational drilling-fluid data. A PFAD-derived branched ester now has contemporary HTHP formulation data. Palm polyol esters have strong lubricant and base-stock evidence. Other fatty-acid esters have laboratory and some field evidence. Yet there is no substantial published record of palm-ester systems operating across multiple offshore deepwater wells under severe HTHP conditions.

Araín and Ridha provide an example of the direction in which biodiesel-based systems are moving through graphene-enhanced sustainable formulations. Agnihotri et al. likewise identify ester fluids and nanotechnology as a developing combination for high-performance drilling, while Singh et al. emphasize standardization, multifunctionality, and field validation as persistent requirements for plant-based nano-structured additives [67,68]. These developments imply that the future palm ester may not be a simple one-component replacement for mineral oil; instead, it may be an engineered fluid in which molecularly optimized esters work together with advanced emulsifiers, rheology modifiers, and nanoparticles.

Discussion and Analysis

FAME and Polyol Esters Should Be Seen as Complementary Technologies

The evidence does not support a simplistic conclusion that polyol esters should replace FAME in every application. FAME has several advantages: established manufacturing capacity, comparatively low molecular weight, relatively low viscosity, excellent inherent lubricity and strong biodegradation potential. It may therefore remain attractive as a major continuous-phase component where temperatures, alkalinity and contamination can be controlled.

Polyol esters address a different part of the design space. Their branched structures provide opportunities to raise flash point, improve viscosity index and enhance thermal and tribological performance. Their greater complexity may, however, raise viscosity and production cost. Certain polyol esters may therefore be more valuable at low concentration as high-performance lubricants than as 100% base oils.

This distinction suggests three viable development routes. Route A is a predominantly FAME or branched-monoester continuous phase optimized through emulsifier and alkalinity design. Route B is a hybrid base in which FAME or 2EH-PFAD is blended with a more thermally robust ester or synthetic hydrocarbon. Route C uses a conventional or branched ester continuous phase combined with palm polyol esters as boundary-lubricating and rheology-modifying additives.

The Strongest Near-Term Candidate May be a Branched PFAD Ester Rather than Commodity FAME

The Pauzi et al. study is strategically important because it points toward a middle ground. A 2-ethylhexyl PFAD ester retains renewable fatty-acid chemistry but introduces branching through the alcohol moiety and makes use of a refinery side stream. The reported flash point, pour point and drilling-fluid performance suggest that this architecture deserves more attention than a simple FAME-versus-polyol binary comparison.

The next experimental step should not merely repeat conventional API tests. The ester should be subjected to long-duration aging at, for example, progressively severe temperature classes, with simultaneous measurement of acid value, ester conversion, soap formation and molecular-weight distribution. This would directly connect chemical degradation to rheological change. Testing in controlled lime, calcium-brine and water-activity matrices would permit hydrolysis kinetics to be mapped rather than simply observed qualitatively.

Polyol Esters are Scientifically Promising but Drilling Evidence Remains Insufficient

Palm-based NPG, TMP and PE esters have a strong rationale arising from lubricant science. Contemporary studies demonstrate favorable viscosity-temperature and tribological characteristics, and PFAD has now been successfully used as a feedstock for polyol esters. General biolubricant studies also show how polyol-ester architectures can be tuned for thermal and tribological performance [69,70].

However, there is a substantial inferential gap between lubricant characterization and drilling-fluid qualification. Drilling systems impose water contact, high alkalinity, emulsifiers, calcium, weighting materials and highly variable shear. A polyol ester that performs exceptionally in a four-ball tribometer may nevertheless destabilize an invert emulsion or generate unacceptable foam. The 2017 palm drilling study already warns against assuming that all polyol esters have equivalent mud compatibility.

Consequently, the strongest scientifically defensible conclusion is that polyol esters are high-priority candidate molecules, not yet proven replacements for existing deepwater synthetic-base fluids. This distinction is important because favorable base-oil or tribological properties cannot substitute for formulation-level validation under realistic pressure, temperature, water activity, and contamination histories.

Comparison with Conventional Synthetic-Base Systems

Mineral oils benefit from mature supply chains and formulation experience but have weaker biodegradation profiles than many esters. Synthetic paraffins and GTL fluids provide clean hydrocarbon chemistry and generally strong chemical stability

but are less readily biodegradable than appropriately designed ester fluids. LAO and isomerized olefin systems can provide good low-temperature properties and hydrolytic resistance but still depend on fossil-derived chemistry in most commercial pathways.

Ester fluids potentially provide superior biodegradation and strong lubricity, but the ester bond introduces hydrolysis risk. Carbonate systems illustrate an alternative design philosophy. Peixoto et al. investigated decyl methyl carbonate as a synthetic drilling-fluid phase and highlighted properties including hydrolytic and material compatibility. The comparison suggests that next-generation palm esters need to compete not merely with diesel but with highly engineered low-toxicity synthetic fluids.

The preferred decision criterion is therefore not a binary choice between renewable and petroleum-derived fluids but a multiobjective assessment integrating technical reliability, environmental fate, operational safety, drilling efficiency, disposal burden, and life-cycle cost. This framing avoids assigning an environmental advantage to a base fluid that creates unacceptable operational or waste-management penalties elsewhere in the drilling system.

A Proposed HTHP Deepwater Design Envelope

A palm-derived drilling fluid should be considered field-ready only after demonstrating acceptable performance within four simultaneous envelopes. These envelopes must be satisfied across the full circulation and aging history rather than at a single laboratory test condition.

The rheological envelope requires sufficiently flat viscosity and yield behavior from cold deepwater temperatures through maximum circulating and static bottomhole temperatures, with ECD remaining inside the planned hydraulic window. The chemical envelope requires resistance to hydrolysis, saponification, and oxidation throughout the expected ranges of water activity, alkalinity, calcium concentration, and aging time.

The mechanical/formulation envelope requires stable emulsion electrical properties, low HTHP filtration, acceptable sag, adequate lubricity, limited foaming, solids tolerance, and elastomer compatibility. The environmental envelope requires favorable biodegradation and ecotoxicity for both fresh and HTHP aged whole fluid formulations.

Figure 3 integrates the four envelopes into the complete deepwater circulation cycle and identifies the usable operating window of a palm-ester drilling fluid. The figure makes clear that failure at any one stage can invalidate otherwise favorable performance elsewhere in the well.

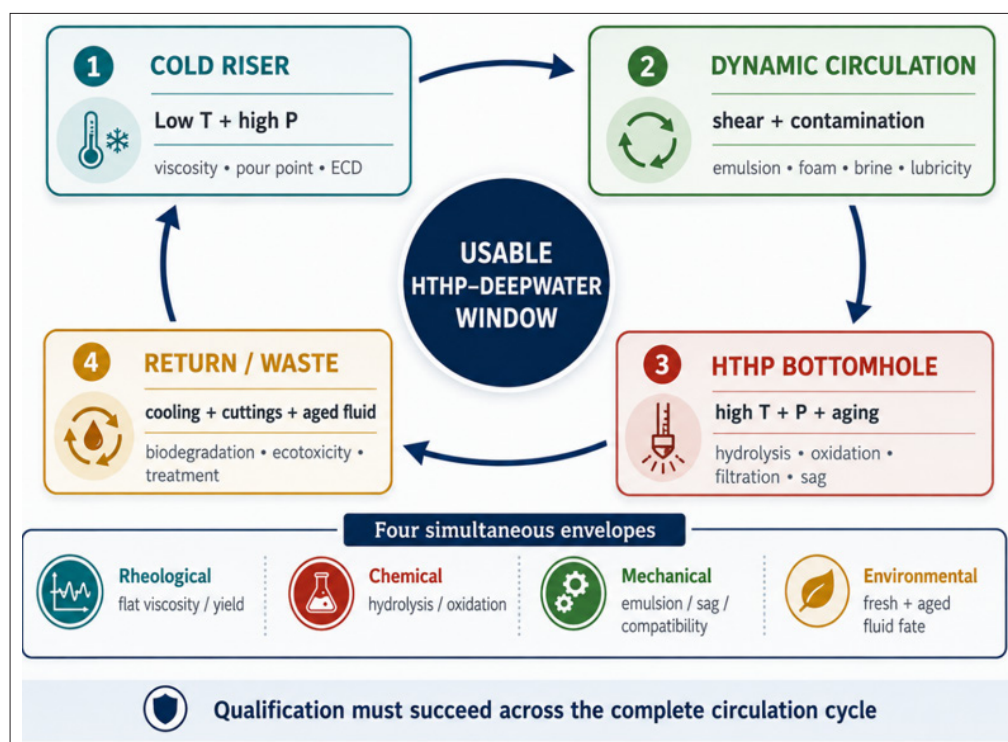


Figure 3: HTHP Deepwater Performance Window

The central requirement is that the formulation remain inside its rheological, chemical, mechanical, and environmental limits through all four stages, not merely at the bottomhole condition. Qualification should therefore test the fluid as a repeatedly heated, cooled, sheared, contaminated, and aged system rather than as a static base oil.

The significance of Figure 3 is that deepwater qualification is a cycle rather than a single extreme point. Repeated heating and cooling may itself generate hysteresis or irreversible structural changes. Future studies should consequently use thermal-pressure cycling protocols rather than only separate hot and cold tests.

A Field-Readiness Ladder

The literature supports a staged qualification program for reducing the current translational uncertainty. Each level should have explicit acceptance criteria so that advancement toward field testing depends on reproducible performance rather than on isolated favorable measurements.

- Level 1 focuses on molecular characterization. It should establish fatty-acid distribution, ester purity, density, the viscosity temperature curve, flash point, pour/cloud point, oxidation stability, hydrolytic stability, and tribological behavior.
- Level 2 evaluates simple mud compatibility. Screening should cover emulsifier interaction, electrical stability, organoclay response, foaming, rheology, and filtration under baseline conditions.
- Level 3 addresses chemical stress testing. Candidate systems should be exposed systematically to lime, calcium brine, seawater, drill solids, cement, and controlled water contamination to identify degradation or emulsion-instability thresholds.
- Level 4 comprises HTHP static aging. Rheology, electrical stability, sag, and filtration should be measured before and after prolonged aging while ester degradation chemistry is quantified in parallel.
- Level 5 evaluates deepwater thermal–pressure cycling. Pressurized rheology should be characterized from approximately seafloor temperatures to maximum circulating temperatures, including repeated heating and cooling cycles.
- Level 6 examines material compatibility. Testing should quantify elastomer swelling, tensile-property retention, hose and seal compatibility, corrosion, and interactions with relevant metallic surfaces.
- Level 7 requires dynamic flow-loop qualification. Pressure loss, ECD, sag, cuttings transport, heat transfer, and emulsion stability should be measured under representative circulating conditions.
- Level 8 moves the technology into pilot field deployment. Controlled land-based or moderate offshore trials should include extensive fluid sampling, operating-data capture, and post-run chemical and materials analysis.
- Level 9 represents multiwell deepwater qualification. At this stage, the formulation should demonstrate repeatable technical performance, logistics, economics, environmental compliance, and waste-management outcomes across multiple wells.

Figure 4 converts the research gap into a practical technology-readiness ladder for palm-derived ester drilling fluids. It also separates promising molecular chemistry from the progressively stronger evidence required for commercial offshore specification.

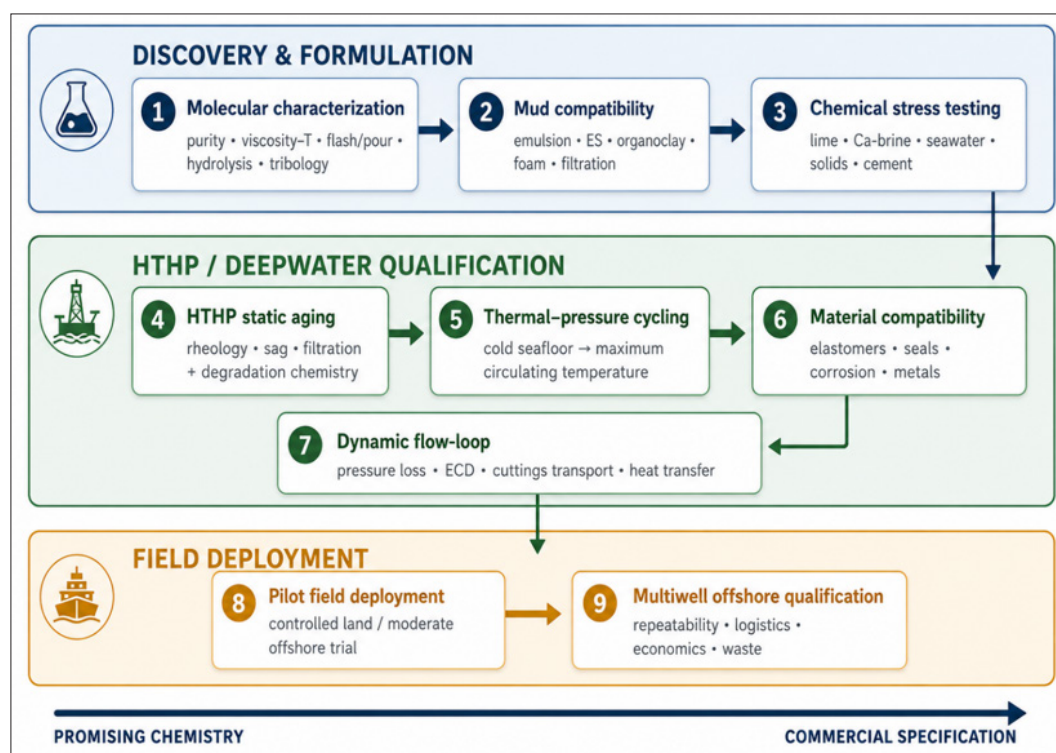


Figure 4: Proposed Technology-Readiness Ladder for Palm-Derived Ester Drilling Fluids

The value of this ladder is its ability to distinguish “promising chemistry” from “field-ready drilling fluid.” The current evidence on palm FAME and 2EH-PFAD is concentrated mainly in the middle laboratory stages, while most palm polyol esters remain closer to the molecular and lubrication stages. Ester-lubricant field evidence such as Dai et al. demonstrates that movement upward is possible, but direct palm-specific offshore evidence is still required.

Priority Research Agenda

Six areas should receive immediate attention. First, hydrolysis kinetics should be measured quantitatively for palm FAME, 2EH-PFAD, NPG, TMP and PE esters under drilling-relevant alkaline brines. Second, pressurized low-temperature rheology should be obtained because conventional atmospheric viscometer results cannot adequately represent deepwater behavior. Third, long-duration HTHP aging should extend beyond 100 °C for candidate PFAD ester systems, with molecular analysis before and after aging. Fourth, elastomer and foaming studies should become routine because these are potentially decisive operational failure mechanisms. Fifth, whole-fluid biodegradation and toxicity testing should compare fresh and HTHP-aged formulations. Sixth, a techno-economic and life-cycle comparison should distinguish commodity FAME, PFAD derived monoesters, polyol esters, synthetic esters, paraffins and mineral oils.

Nanotechnology may provide an additional route for controlling emulsion stability and HTHP performance. Environmentally oriented nanofluid research has produced promising improvements in rheology, filtration, and stability while modern drilling-fluid reviews increasingly anticipate combinations of biodegradable base fluids and advanced nanomaterials. Such systems, however, should be assessed for nanoparticle environmental fate, dispersion stability, and recovery or disposal requirements rather than assuming that the addition of nanomaterials automatically improves sustainability.

Conclusion

Palm-oil-derived esters represent a credible platform for developing more biodegradable drilling fluids, but the evidence does not support treating them as immediate universal replacements for mineral-oil or established synthetic-base fluids. Their value lies in the chemical diversity that can be generated from palm fatty acids rather than in the renewable feedstock alone.

FAME provides an accessible first-generation route. It combines relatively low viscosity, strong lubricity, high flash-point potential and biodegradability, and foundational drilling-fluid work has demonstrated genuine formulation feasibility. Its principal weaknesses are equally clear: water and alkaline environments can promote hydrolysis and saponification, while fatty-acid unsaturation introduces oxidation sensitivity. These limitations become more serious as temperature, aging duration and contamination severity increase.

Branched PFAD derived monoesters represent an especially promising second-generation pathway. Contemporary drilling-fluid evidence demonstrates that 2EH-PFAD can be incorporated into technically competitive ester-based formulations, while use of a refinery side stream improves the circularity proposition. Nevertheless, existing HTHP evaluation remains below the temperature range required to demonstrate severe HTHP capability and has not yet reproduced full deepwater temperature-pressure cycling.

Palm-derived NPG, TMP and PE polyol esters constitute a third and potentially more sophisticated pathway. Their molecular architectures can provide high viscosity indices, strong lubricity, reduced volatility and enhanced thermal potential. Recent PFAD derived polyol and estolide research further expand this design space. However, their strongest evidence currently comes from lubrication and base-oil studies rather than realistic drilling-fluid

qualification. They should therefore be treated as high-priority candidate base stocks or functional additives rather than as proven offshore replacements.

The most promising development strategy may ultimately be hybrid rather than substitutional: a relatively low-viscosity branched ester as the principal continuous phase, combined with selected palm polyol esters and tailored emulsifier/rheology packages to provide lubricity and temperature resistance. Such a system would exploit the complementary properties of different ester structures.

Future research should consequently move away from isolated measurements of biodegradability or room-temperature lubricity and toward integrated qualification. Long-duration HTHP aging, alkaline hydrolysis kinetics, deepwater pressurized rheology, contamination tolerance, foam control, elastomer compatibility, whole-fluid ecotoxicity, dynamic circulation and multiwell field testing are the critical missing steps. Until these are completed, palm-derived esters should be regarded not as fully qualified drop-in replacements but as a highly promising molecular platform from which the next generation of environmentally responsible HTHP and deepwater drilling fluids may be engineered.

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