

From Palm Triglycerides to Performance-Engineered Fluids: Molecular Design, Green Tribology, Nano-Additives, Oxidation Control, and Commercial Readiness of Palm-Based Biolubricants-A Critical Review

Loso Judijanto

IPOSS Jakarta, Indonesia

Corresponding author

Loso Judijanto, IPOSS Jakarta, Indonesia.

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ABSTRACT

Industrial lubrication sits at the intersection of machinery reliability, energy efficiency, resource use, and environmental protection. Palm oil and its derivatives represent promising renewable feedstocks for industrial biolubricants because their ester-rich molecular structures provide strong surface affinity and favorable lubricity, while an established oleochemical industry offers multiple pathways for molecular transformation. However, native palm oils cannot simply replace petroleum lubricants across industrial applications because oxidative degradation, temperature-dependent rheology, low-temperature behavior, hydrolytic stability, additive compatibility, and severe-contact performance remain important constraints. This critical qualitative literature review synthesizes research published principally between 2020 and 2026 to examine how palm oil, palm olein, palm kernel oil, palm stearin, palm fatty acid distillate, fatty-acid esters, polyol esters, epoxidized derivatives, and estolides can be converted into performance-engineered lubricating fluids. The analysis integrates molecular structure-property relationships, chemical modification, antioxidant engineering, tribochemical mechanisms, nano-additives, and application-specific requirements. Particular attention is given to hydraulic systems, bearings, metalworking, refrigeration, agricultural machinery, marine applications, and emerging electric-vehicle drivetrains. The review argues that commercial viability depends not on biodegradability alone but on matching molecular architecture and formulation to specific operating environments, followed by accelerated ageing, component validation, standards compliance, life-cycle assessment, and techno-economic qualification. A technology-readiness framework is proposed for progressing palm-derived lubricants from promising laboratory formulations toward high-performance industrial fluids.

Keywords: Palm Oil, Biolubricant, Green Tribology, Palm Fatty Acid Distillate, Polyol Ester, Estolide, Nano-Additives, Oxidation Stability, Industrial Machinery, Sustainable Lubrication

JEL Classification: L64 Other Machinery, L65 Chemicals, Rubber, Drugs and Biotechnology, O32 Management of Technological Innovation and R&D, Q55 Technological Innovation, Q56 Environment and Development, Sustainability

Introduction

Lubrication is an enabling technology of modern industry because virtually every machine containing moving interfaces must manage friction, wear, heat generation, surface fatigue, or some combination of these phenomena. Lubricants decrease direct asperity contact, control friction, remove or redistribute

heat, protect surfaces against corrosion, carry contaminants, and extend component service life. Their contribution to industrial sustainability therefore extends beyond the lubricant itself: even small improvements in frictional performance or wear protection may reduce energy consumption, component replacement, maintenance downtime, and material demand across machinery life-cycles. This systems perspective is the intellectual basis of green tribology, which treats lubrication not merely as a maintenance input but as part of the environmental and energy performance of mechanical systems [1-4].

Conventional mineral lubricants possess several advantages developed through more than a century of formulation experience, including broad availability, predictable viscosity grades, additive compatibility, and proven performance under demanding operating conditions. Their environmental

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disadvantages are nevertheless important, particularly in total-loss applications, agricultural machinery, forestry equipment, marine systems, metalworking operations, and other situations in which leakage or operational loss can introduce lubricant into soil or water. The sustainability question is therefore not limited to depletion of petroleum resources. It concerns the entire life-cycle of lubrication, including feedstock production, formulation, operational efficiency, uncontrolled releases, disposal, biodegradation, toxicity, and replacement frequency [5-8].

Vegetable oils have attracted sustained interest as lubricant feedstocks because triglycerides contain long hydrocarbon chains combined with polar ester groups. The non-polar portions can provide a lubricating fluid phase, whereas the polar ester functionalities favor adsorption at metallic surfaces. This molecular combination can produce strong boundary lubrication and high viscosity indices. Vegetable oils also generally exhibit high flash points, relatively low volatility, renewable origins, and substantially greater biodegradability than many conventional mineral oils. However, their use exposes a fundamental molecular trade-off: unsaturation that helps maintain fluidity also creates chemically reactive sites susceptible to oxidative attack, while increased saturation can improve oxidation resistance but encourage crystallization and poor cold-flow behavior [9-12].

Palm oil deserves separate treatment within this broader biolubricant field. Palm-derived feedstocks are not chemically homogeneous. Refined palm oil, palm olein, palm mid olein, palm stearin, palm kernel oil (PKO), palm fatty acid distillate (PFAD), palm methyl esters, and oleochemical derivatives present substantially different saturation levels, molecular architectures, viscosity behavior, and modification opportunities. These differences make “palm oil as a lubricant” an overly broad concept. The more technically useful question is how specific palm fractions and oleochemical intermediates can be converted into molecules and formulations designed for particular lubrication regimes and machinery requirements [13,14].

Recent research demonstrates this transition from feedstock substitution to molecular engineering. High-oleic palm methyl esters have been converted into trimethylolpropane (TMP) esters through enzymatic transesterification; PFAD has been transformed into neopentyl-glycol and 2-ethylhexyl esters; PKO has undergone TMP transesterification and epoxidation-esterification; and palm-derived pentaerythritol esters have been investigated for refrigeration lubrication. These studies show that the oleochemical pathway is increasingly concerned with creating a desired molecular architecture rather than using the native triglyceride unchanged [15-19].

The frontier is advancing further. PFAD can now be considered not merely a refinery side-stream but a potentially valuable lubricant carbon source. A 2026 study directly valorized PFAD through estolide formation followed by esterification with 2-ethylhexanol, reporting combinations of lubricity, high viscosity index, enhanced oxidation behavior, and markedly improved low-temperature performance. The distilled PFAD estolide ester achieved a reported pour point of $-21\text{ }^{\circ}\text{C}$, illustrating how branching and estolide architecture can transform the performance envelope of a feedstock whose

original composition would otherwise create low-temperature limitations [20].

At the same time, additive engineering is moving from conventional antioxidants and viscosity modifiers toward nanoscale tribological modifiers. Palm-derived formulations containing CuO, TiO₂, graphite, h-BN and other nanoscale materials have been studied for friction reduction, anti-wear protection, thermal behavior, and component performance. Yet nano-additives introduce a new engineering problem: a nanoparticle that produces excellent results during a short tribometer experiment is not necessarily a commercially viable lubricant additive if it aggregates, sediments, blocks filters, changes rheology, reacts with elastomers, or presents environmental hazards during use or disposal [21-24].

The distinction is important because an industrial lubricant is a functional system rather than a single chemical substance. Base-oil architecture, antioxidants, anti-wear agents, extreme-pressure additives, corrosion inhibitors, viscosity modifiers, pour-point depressants, dispersants, nanoparticles, contaminants, water, surfaces, temperatures, speeds and loads interact. Optimization of one performance indicator can therefore create penalties elsewhere. A formulation with exceptionally low friction may be unsuitable because of inadequate oxidation life; a highly stable ester may be incompatible with a refrigerant; a nanoparticle may improve wear but destabilize during storage; and a chemically modified oil may meet laboratory viscosity requirements while remaining economically impractical to manufacture at commercial scale [25-27].

This critical qualitative review consequently addresses a central question: **Can palm-derived lubricants progress from renewable and biodegradable substitutes to technically competitive, performance-engineered industrial fluids?** To answer it, the review synthesizes evidence across feedstock chemistry, molecular modification, green tribology, oxidation science, additive engineering, nanolubrication, component applications, environmental performance and technology readiness. Unlike reviews that primarily catalogue oils, reaction conditions, or friction coefficients, the present analysis proposes an integrated **molecule-to-market framework** in which lubricant performance is understood as a chain connecting molecular architecture to formulation, tribochemical behavior, component qualification and commercialization.

Literature Review: Conceptual and Theoretical Foundations Green Tribology and the Function of Lubricants

Tribology concerns friction, lubrication and wear at interacting surfaces. Under full-film hydrodynamic lubrication, surfaces are largely separated by a fluid film, making viscosity and rheological response crucial. Mixed lubrication combines partial fluid separation with asperity interaction, while boundary lubrication occurs when the fluid film becomes sufficiently thin that molecular adsorption, additives and tribochemical films control surface protection. An industrial lubricant may encounter several regimes during start-up, steady operation, transient loading, temperature changes or contamination events, making performance under one standardized test insufficient to characterize complete application suitability [2,11].

Vegetable oils are especially attractive in boundary lubrication because ester groups and other polar functionalities interact strongly with metallic surfaces. Adsorption can produce relatively ordered films that separate opposing asperities and reduce adhesive wear. The hydrocarbon chains extend away from the surface and contribute to cohesive film formation. This mechanism helps explain why vegetable oils can show excellent friction behavior even when other properties, such as oxidation life or low-temperature flow, are less favorable. However, adsorption strength, molecular packing and film persistence depend on fatty-acid structure, temperature, sliding conditions and competition among surface-active additives [10,4].

Green tribology expands this analysis by asking whether the lubricant reduces the combined environmental burden of a tribosystem. Biodegradability and renewable carbon are important but incomplete criteria. A lubricant that biodegrades rapidly but oxidizes so quickly that it must be replaced repeatedly may not provide an optimal life-cycle outcome. Likewise, an environmentally benign base oil can lose part of its advantage if its formulation depends on persistent or toxic additives. Sustainable lubricant design should therefore integrate energy efficiency, wear reduction, service interval, feedstock impacts, additive hazards, leakage consequences, regeneration possibilities and end-of-life management [6,7,28].

Molecular Architecture of Palm-Derived Feedstocks

Palm oil contains triglycerides carrying a mixture of saturated and unsaturated fatty-acid chains, prominently palmitic and oleic components, whereas palm kernel oil is more strongly characterized by shorter-chain lauric-type fatty acids. Fractionation generates olein and stearin streams with different thermal behavior and fatty-acid distributions. Consequently, refined palm oil, palm olein, palm mid olein and palm stearin cannot be expected to display identical viscosity, crystallization, oxidation or boundary-film characteristics. Four-ball experiments comparing palm fractions have demonstrated that changes in saturated and unsaturated fatty-acid composition produce measurable differences in friction, wear and surface condition [14].

The molecular explanation involves several interacting variables. Increasing chain length tends to increase intermolecular interaction and viscosity. Polar ester groups increase affinity for metal surfaces. Unsaturated bonds introduce kinks that disrupt efficient molecular packing and can preserve fluidity at lower temperature; however, they also represent preferential locations for oxidative reactions. Saturated chains are chemically more resistant to oxidation but may crystallize readily. Branching disrupts packing and can depress melting or pour points. Molecular symmetry, the number and spatial arrangement of ester groups, and steric hindrance can further influence viscosity, polarity, miscibility and phase transitions [10,11].

Palm stearin illustrates the importance of treating the feedstock as a molecular platform rather than assigning it a fixed lubricant identity. A 2025 investigation compared natural palm stearin, palm stearin methyl ester and epoxidized palm stearin methyl ester and found substantial differences in rheological, thermal and boundary-lubrication behavior. The epoxidized methyl ester delivered the lowest friction coefficient and wear rate under

the most demanding tested sliding condition, demonstrating that changes in chemical architecture can alter lubrication-film formation as well as bulk physical properties [29].

PFAD represents another distinct platform. Generated during physical refining, PFAD contains a high fraction of free fatty acids rather than intact triglycerides, allowing routes that would be less direct for native oil. Its status as a side-stream can also improve the resource-efficiency argument by reducing direct competition between edible oil and industrial lubricant manufacture. Studies have produced PFAD-derived NPG esters, polyhydric-alcohol esters and 2-ethylhexyl esters, while the recent estolide route further broadens the range of achievable molecular structures [30,17,19,20].

Figure 1 summarizes the conceptual shift proposed in this review. Palm biolubricant development should begin with the functionality required by the target machine rather than with the assumption that a specific palm fraction must simply replace mineral oil. Feedstock composition determines available molecular pathways, but chemical architecture, formulation and application testing ultimately determine technical value.

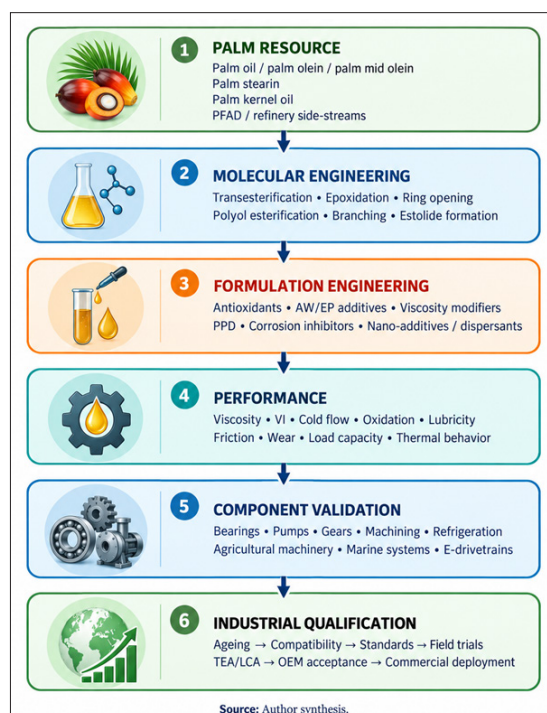


Figure 1: Molecule-to-market architecture for palm-based industrial biolubricants

The figure highlights why a palm biolubricant should not be evaluated only through coefficient of friction or biodegradability. Commercialization is a sequential evidence problem. A formulation must survive the entire pathway from chemical synthesis through storage and ageing to component-level operation, while environmental and economic claims must remain defensible at production scale.

Method

This study adopts a **critical qualitative literature review** design. It is intentionally not structured as a systematic literature review and does not claim exhaustive coverage, PRISMA-based screening, quantitative meta-analysis or pooled effect estimation.

The purpose is interpretive integration across research domains that are frequently separated in the literature, particularly oleochemistry, lubricant chemistry, tribology, nanotechnology, mechanical engineering, sustainability analysis and industrial scale-up.

Literature identification was concept-driven and iterative. Priority was given to peer-reviewed journal literature published between 2020 and 2026 addressing palm-derived or vegetable-oil-based lubricants, with palm-specific research treated as the core evidence. Broader vegetable-oil studies were included where they clarified transferable structure-property relationships, oxidative pathways, chemical modification mechanisms, nanoparticle behavior, tribological mechanisms, or application requirements not yet investigated comprehensively with palm-derived formulations. Relevant literature was identified through combinations of terms including palm oil biolubricant, palm olein tribology, palm kernel oil lubricant, palm stearin biolubricant, palm fatty acid distillate lubricant, polyol ester biolubricant, epoxidized vegetable oil lubricant, estolide lubricant, vegetable oil nanolubricant, bio-based hydraulic fluid, metalworking biolubricant, and electric vehicle biolubricant.

The review prioritized studies reporting interpretable physicochemical or tribological outcomes, including viscosity, viscosity index, pour point, flash point, oxidation behavior, thermal stability, friction coefficient, wear scar or wear rate, load-carrying, tribofilm characterization, rheological behavior, nanoparticle dispersion, component performance or application compatibility. Reviews were used to establish broader theoretical patterns and identify cross-feedstock mechanisms, whereas primary studies were emphasized when drawing palm-specific conclusions.

Thematic coding organized the evidence into seven analytical domains: (1) feedstock architecture; (2) molecular modification; (3) structure-property and tribochemical relationships; (4) oxidation and additive engineering; (5) nano-enhancement and dispersion stability; (6) application-specific qualification; and (7) commercialization and technology readiness. Rather than simply tabulating study results, conflicting findings were interpreted in relation to differences in fatty-acid composition, molecular architecture, additive concentration, tribometer configuration, contact materials, load, sliding speed, temperature and ageing condition.

The qualitative synthesis therefore uses a mechanism-oriented logic. If two studies report different coefficients of friction for nominally similar vegetable-oil lubricants, the discrepancy is not treated automatically as inconsistency. Instead, potential moderators—such as saturation profile, molecular polarity, viscosity, test regime, surface material, additive dispersion and temperature—are considered. This approach is especially appropriate for tribology because experimental outcome is produced by a coupled lubricant-surface-operating-condition system rather than by lubricant chemistry alone [3,10,26].

Results: Thematic Findings

Theme I: Palm Oil Is a Family of Lubricant Feedstocks, Not a Single Base Oil

The first major finding is that palm-derived lubrication should

be conceptualized as a portfolio of feedstocks. Native palm oil can provide excellent boundary-film behavior, but palm olein fractions offer different fluidity, palm stearin offers a more saturated but higher-melting platform, PKO provides shorter-chain lauric structures, and PFAD provides concentrated free fatty acids suitable for direct esterification chemistry. The optimum feedstock therefore depends on whether the design priority is lubricity, viscosity, low-temperature flow, oxidation resistance, synthesis simplicity, feedstock cost or circular utilization of refinery side-streams [13,15,30].

Experiments with different palm fractions reinforce this conclusion. Zulhanafi et al. compared RBD palm oil, double-fractionated palm olein and palm mid olein and found composition-dependent tribological behavior [14]. Such findings caution against using a single generic fatty-acid descriptor to predict performance. Under boundary lubrication, molecular adsorption, fluid viscosity, chain packing, temperature and contact severity interact. A higher saturated fraction may improve film organization or oxidation resistance in one regime while worsening cold-flow behavior in another.

PKO provides a useful contrasting example. Egbuna et al. used TMP transesterification and epoxidation-esterification to modify PKO into candidate lubricant base stocks, achieving properties consistent with an ISO viscosity-grade range [15]. The importance of this work is not that one modification route universally dominates, but that PKO's native lauric chemistry can be moved into industrially more useful property windows by changing alcohol functionality and molecular architecture.

PFAD potentially addresses a different barrier: feedstock economics and industrial sustainability. Using a refining side-stream avoids dedicating the highest-value edible fraction to lubricant production. Ng et al. converted PFAD into neopentyl-glycol esters using a reusable solid acid catalyst and reported an ester yield of approximately 82% under optimized conditions; selected properties satisfied relevant two-stroke lubricant requirements [17]. Pauzi et al. demonstrated non-catalytic PFAD esterification with 2-ethylhexanol, followed by purification, reporting a high viscosity index and physicochemical properties suggesting potential use in low-viscosity hydraulic applications [19].

PFAD's most interesting emerging role may be as a precursor for branched estolide systems. The 2026 work of Pitakjakpipop-Krasae et al. is significant because direct PFAD utilization reduces the need for prior hydrolysis or fractionation. Estolide formation creates larger, branched structures, while esterification with 2-ethylhexanol further modifies viscosity and crystallization behavior. This represents a shift from treating PFAD as a low-value by-product toward viewing its mixed fatty-acid composition as an oleochemical resource for high-value base-oil design [20].

Theme II: Molecular Modification Is the Central Performance-Engineering Tool

The literature consistently shows that chemical modification is necessary when palm-derived oils are expected to perform outside relatively mild lubrication environments. Native

triglycerides contain structural features that create competing advantages and liabilities. Ester groups promote surface affinity, but the β -hydrogen arrangement of the glycerol backbone and unsaturated carbon-carbon bonds contribute to thermo-oxidative vulnerability. Modification therefore seeks to preserve desirable polarity and lubricity while redesigning the portions of the molecule responsible for oxidation, crystallization or inadequate viscosity behavior [9,31,32].

Transesterification is among the most established pathways. Conversion first to fatty-acid methyl esters and subsequently to polyol esters can remove the glycerol structure and create molecules with improved thermal and rheological behavior. TMP and pentaerythritol are particularly important because their branched polyol structures can generate multiple ester functionalities without problematic β -hydrogen arrangements. Plant-based TMP esters are consequently used as a central platform in modern biolubricant research [33,25].

Palm-specific evidence supports this strategy. Abd Wafti et al. synthesized TMP ester from high-oleic palm methyl ester using immobilized Lipozyme 435 [16]. The optimized enzymatic route achieved a high proportion of triester while simplifying downstream purification, demonstrating that biocatalysis can improve not only environmental process characteristics but potentially production economics where separation and catalyst management are significant cost components.

Enzymatic processing more broadly offers advantages including lower reaction temperatures, substrate selectivity and reduced dependence on strong homogeneous catalysts. However, industrial adoption requires attention to enzyme cost, immobilization stability, inhibition, water management, reaction equilibrium, mass transfer, catalyst recycling and long-term productivity. The greenest laboratory pathway is not automatically the lowest-impact commercial pathway if enzyme replacement or solvent consumption becomes excessive. Accordingly, process sustainability should be evaluated through mass and energy balances rather than inferred solely from the biological origin of the catalyst [34-36].

Epoxidation provides a second major strategy by converting vulnerable carbon-carbon double bonds into oxirane groups. The process can increase resistance to oxidation and creates chemically reactive functionality for subsequent ring-opening reactions. However, epoxidation illustrates the multi-objective nature of lubricant design: changing unsaturation can alter viscosity, polarity, low-temperature behavior and tribofilm interactions, and an apparent improvement in oxidation stability does not guarantee simultaneous improvement in every lubrication property [37,32].

This complexity is visible in palm stearin research. Afifah et al. found that palm stearin, its methyl ester and its epoxidized methyl ester exhibited distinct rheological and tribological behaviors [29]. Epoxidized palm stearin methyl ester delivered favorable friction and wear performance in the reported boundary-lubrication experiments, yet thermal and oxidation indicators did not follow a simple monotonic hierarchy across all formulations. This finding is valuable because it demonstrates

that “more chemically modified” does not automatically mean “better” in every metric; the relevant comparison depends on the target duty cycle and failure mode.

Branching and estolide formation represent a third strategy particularly relevant to overcoming cold-flow limitations. Straight and highly saturated chains can pack efficiently, promoting crystallization at lower temperatures. Branching interrupts molecular packing and therefore lowers the tendency to crystallize. Estolide structures add branching through fatty-acid-derived linkages and can combine good lubricity with favorable viscosity-index and low-temperature properties. Their drawback has historically included synthetic complexity and cost when purified fatty acids are required [38,4].

The PFAD estolide pathway changes this calculation because PFAD itself already provides free fatty acids. Pitakjakkpipop-Krasae et al. showed that PFAD could be used directly for estolide formation and subsequent 2-ethylhexyl esterification [20]. The resulting products demonstrated how molecular branching can simultaneously influence lubricity, viscosity index, oxidation response, and pour point. This reinforces the central argument that palm-derived lubricant development is increasingly a molecular architecture problem rather than a feedstock substitution problem.

The various modification routes are not interchangeable. Figure 2 maps each major route to the molecular limitation it primarily addresses and the trade-offs that must subsequently be tested.

The implication is that chemical modification should be selected from a desired performance vector rather than a single property. For example, maximizing oxidation stability while creating an unacceptable pour point does not constitute successful lubricant engineering. The preferred pathway is therefore application-specific and should be determined through simultaneous optimization of several properties.

Theme III: Oxidation Stability Is a Dynamic Tribological Problem

Oxidation is frequently described as one disadvantage of vegetable oils, but this wording understates its significance. Oxidative degradation progressively changes the lubricant that actually reaches the contact interface. Initiation generates radicals, hydroperoxides and other primary oxidation products; decomposition then produces acids, aldehydes, ketones, oligomers, polymers and deposits. These transformations alter viscosity, polarity, acidity, volatility and surface interactions. Oxidation therefore couples chemical ageing to tribological ageing [9,39].

The rate of oxidation is strongly affected by fatty-acid unsaturation, temperature, oxygen availability, catalytic metals, water and existing degradation products. Polyunsaturated structures are generally more susceptible than monounsaturated and saturated chains because allylic and bis-allylic positions facilitate radical processes. High-oleic feedstocks can consequently provide useful lessons for palm lubricant design: increased oleic content can offer a compromise between the crystallization tendency of highly saturated structures and the oxidation vulnerability of highly polyunsaturated oils [39,12].

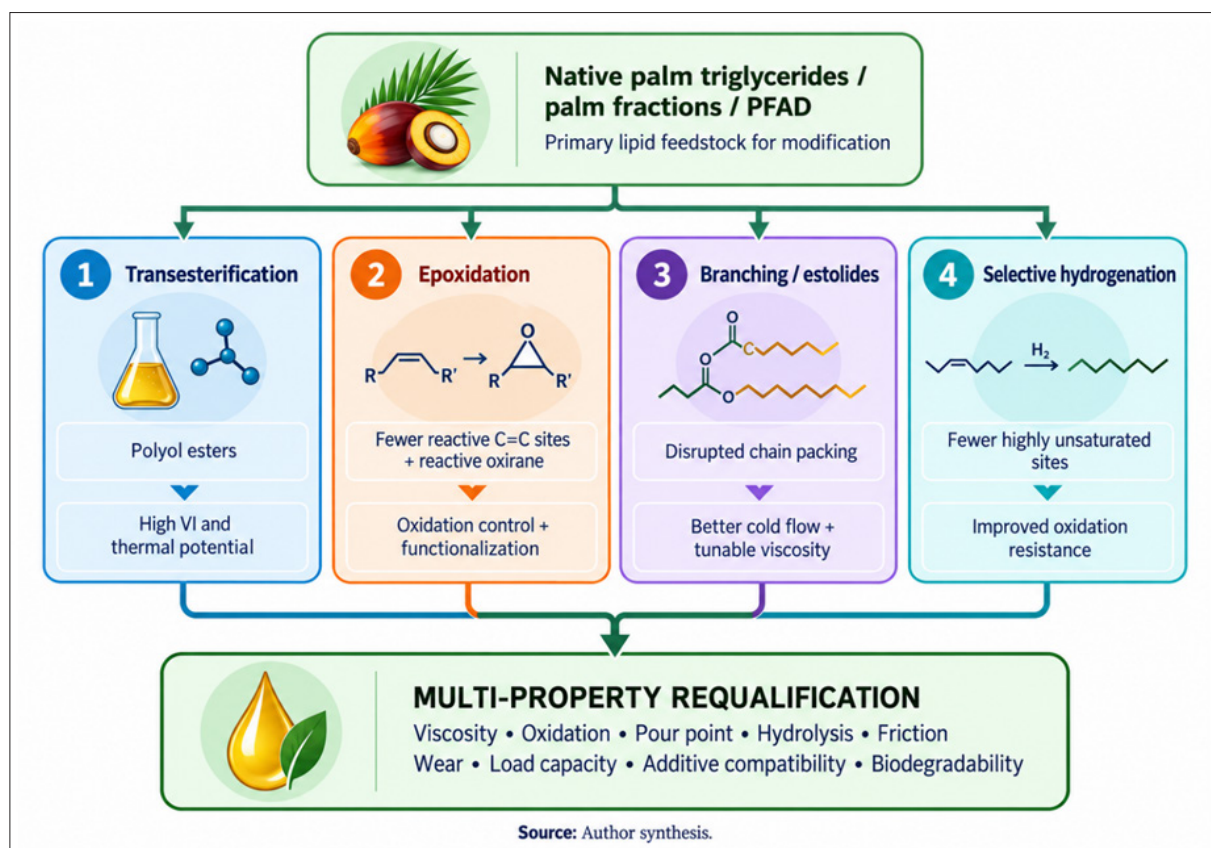


Figure 2: Molecular modification routes and targeted lubricant functions

Antioxidants provide one response. Radical-scavenging additives such as phenolic antioxidants can interrupt oxidation chains, while synergistic antioxidant systems may extend induction periods more effectively than single additives. Encinar et al. Working with a high-oleic pentaerythritol biolubricant, showed that antioxidant addition could materially improve oxidative stability while preserving important lubricant properties [40]. Although the feedstock was not palm-derived, the mechanism is directly relevant to palm esters because oxidation control depends on similar ester and fatty-acid chemistry.

Palm mid-olein provides direct application evidence. Norazman et al. Evaluated palm mid-olein containing tertiary-butylhydroquinone as antioxidant and ethylene-vinyl acetate as a viscosity improver in hydrodynamic journal-bearing experiments [41]. The treated formulation provided favorable oil-film pressure, load-carrying capacity and friction behavior relative to unmodified palm mid-olein under the tested conditions. This demonstrates why additive engineering should be integrated with base-oil chemistry rather than treated as a final corrective step.

Chemical modification and antioxidant addition should also be viewed as complementary rather than competing strategies. Modification can remove or transform intrinsically vulnerable structural sites, while antioxidants slow reactions that remain possible during storage and operation. A chemically stable base stock may permit lower antioxidant loading, potentially improve biodegradability or reduce formulation complexity. Conversely, attempting to compensate for a highly oxidation-prone base oil entirely through additives may create cost, toxicity and compatibility penalties [9,8,32].

An important research gap is the limited number of studies that perform tribological testing **after controlled oxidative ageing**. Many formulations are tested when fresh, producing friction and wear data that may not represent lubricant performance after hundreds or thousands of operating hours. Future research should therefore integrate accelerated oxidation, viscosity growth, acid-number development, spectroscopic oxidation markers and subsequent tribological testing. An industrially useful lubricant must protect surfaces not only on day one but throughout its intended service interval.

Theme IV: Tribological Performance Emerges from Molecular Structure and Operating Regime

One of the most important lessons from the reviewed literature is that coefficients of friction and wear values should never be interpreted independently of test conditions. Friction depends on load, sliding speed, temperature, contact geometry, surface roughness, materials, lubrication regime and lubricant viscosity. A formulation performing well in a four-ball boundary test may behave differently in a hydrodynamic bearing or gear contact. This is why standardized benchmark fluids and carefully reported operating conditions are indispensable for comparing studies [3,10].

Palm-derived oils can perform particularly well in boundary and mixed regimes because polar ester molecules adsorb on metal and generate protective films. Zulhanafi et al. Showed that palm fractions with different fatty-acid distributions produced different friction and wear behavior in four-ball testing [14]. More recent palm-stearin results similarly demonstrate that modification changes the nature of the lubrication film rather than simply changing viscosity [29].

Hydrodynamic applications reveal a different performance balance. In a journal bearing, adequate viscosity and viscosity-temperature response are necessary to build load-supporting fluid pressure. Palm mid-olein has been evaluated directly in journal-bearing rigs, with studies reporting favorable friction characteristics compared with mineral reference fluids under particular operating conditions. The later addition of antioxidant and viscosity modifier further strengthened the evidence that palm-derived oils can be formulated around component-level hydrodynamic requirements rather than evaluated solely with small-scale tribometers [42,41].

Metal-forming research also supports application specificity. Yahaya et al. Modelled palm mid-olein behavior in cold forging using DEFORM-3D, connecting tribological behavior with deformation and process conditions [43]. Such work represents a useful transition from generic lubricant characterization toward manufacturing-process integration. Vegetable-oil nanolubricant research in machining similarly shows that viscosity, wettability, heat transfer, anti-wear properties and nanoparticle transport must be considered simultaneously [44].

The broader vegetable-oil literature further demonstrates that high-oleic composition can improve temperature-dependent rheological and frictional performance. Saka et al. Comparing high- and low-oleic vegetable oils with commercial lubrication references, found that fatty-acid profile materially influenced rheo-thermal behavior and friction [12]. Such results reinforce the relevance of high-oleic palm fractions or selectively designed palm esters where thermal stability and fluidity must be balanced.

Theme V: Nano-Additives Offer Large Gains but Create a Dispersion-Stability Bottleneck

Nano-additives are among the fastest-moving areas of sustainable lubrication research. Metal oxides, graphene and graphite materials, h-BN, MoS₂ and nanocellulose can act through several proposed mechanisms. Near contact regions, particles may roll or slide between asperities, fill surface valleys, polish roughness, participate in protective tribofilm formation, or improve heat transfer. The dominant mechanism depends on particle size, morphology, chemistry, concentration, surface modification and tribological environment [45,3,24,46].

Experiments in non-palm vegetable oils demonstrate the range of possibilities. Cortes et al. studied SiO₂ and TiO₂ nanoparticles in sunflower oil; Ranjan et al [47]. Investigated TiO₂/g-C₃N₄ nano-additives; Omrani et al [48]. Examined graphene additives; Fernández-Silva et al [49]. Investigated nanocellulose-based ecolubricants; and Fuadi et al [50]. Reported tribological enhancement from graphene nanoplatelets incorporated into a bacterial-cellulose/polyolester lubricant [51]. Collectively, these studies demonstrate that nanoscale solids can materially affect friction and wear, but they also show that the optimum concentration and mechanism are formulation-specific.

Palm-specific studies make this field particularly relevant. Rajaganapathy et al. Reported improved friction, wear and thermal-related properties when CuO and TiO₂ were introduced into vegetable-oil systems including palm oil [21]. Amiruddin et al. Moved beyond small-contact tribometers by examining

roller-chain wear with palm-oil-based h-BN nanoparticles, illustrating an early attempt at component-relevant nanobiolubrication [22].

Azman et al. Provided a more mechanistic example using graphite nanoplatelets in PKO-based lubricant [23]. Addition of oleic acid as a surfactant promoted graphite exfoliation and was associated with reductions in coefficient of friction and wear-scar diameter relative to the PKO base fluid. The authors connected performance to structural transformation of graphite and development of a more ordered tribofilm, emphasizing that nanolubrication is not simply a matter of particles acting as miniature ball bearings.

Nano-additives therefore introduce tribochemistry within tribochemistry: interactions occur between the palm-derived fluid, particle surface, dispersant, metallic substrate, wear debris and temperature-dependent reaction products. This complexity helps explain why concentration effects are often non-linear. At low concentration, too few particles may reach the contact region; at an intermediate concentration, beneficial film formation or mending may occur; at excessive concentration, aggregation or abrasive behavior may counteract the benefit [52,26].

Dispersion stability is accordingly one of the most important commercialization barriers. A formulation that remains homogeneous for a few hours during laboratory testing may sediment during warehouse storage or prolonged operation. Dhanola and Garg highlighted the need to evaluate aggregation and rheology as fundamental nanolubricant characteristics [52]. This concern is especially relevant for machinery containing fine filters and small oil passages, where agglomerates can create operational problems even if they reduce friction in a standardized tribometer.

A 2025 palm-olein/TiO₂ investigation explicitly addressed this issue. Nugroho et al. optimized ultrasonication and evaluated sedimentation, UV-visible absorbance, and zeta potential over an extended stability period. Sixty minutes of ultrasonication provided the most favorable reported dispersion condition, illustrating that formulation-process parameters can be as important as nanoparticle chemistry itself [53].

Figure 3 places nano-additive benefits and risks in a single framework. The central message is that friction reduction alone cannot establish industrial readiness.

The figure indicates that successful nanolubrication requires two optimization loops. The first concerns tribological effectiveness; the second concerns formulation stability, equipment compatibility and environmental acceptability. Only formulations passing both loops should progress toward field testing.

Theme VI: Different Machines Require Different Palm-Based Lubricants

Hydraulic systems

Hydraulic fluids transfer power while simultaneously lubricating pumps, valves and actuators, controlling corrosion, removing heat and maintaining predictable viscosity across temperature. These combined functions make hydraulics one of the most

demanding but attractive targets for bio-based esters. High viscosity index, anti-wear behavior, oxidation life, hydrolytic stability, seal compatibility, low-temperature flow and air-release behavior can all influence system reliability [27].

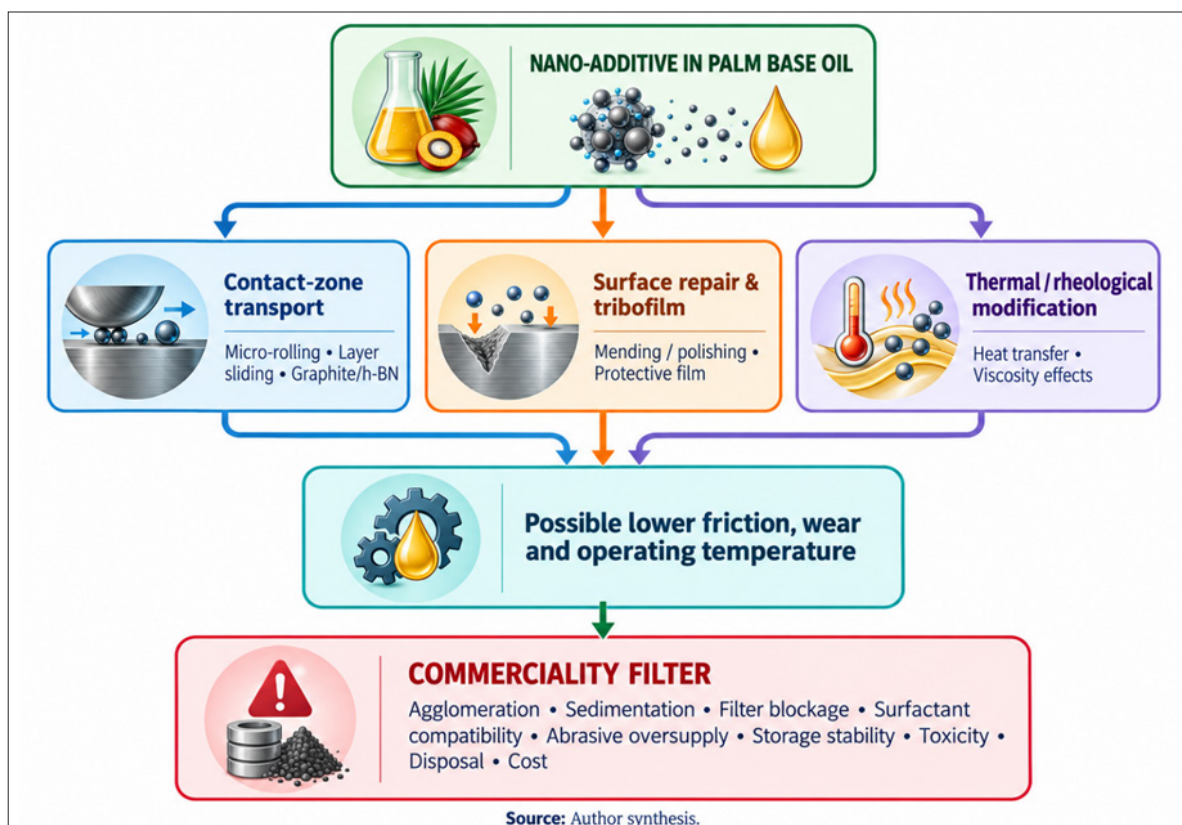


Figure 3: Nano-additive performance mechanisms and scale-up constraints

PFAD-derived 2-ethylhexyl ester illustrates a possible pathway to lower-viscosity hydraulic applications. Pauzi et al. Reported physicochemical properties suggesting an ISO VG 10-type application window, including a high viscosity index [19]. However, meeting basic viscosity classification is only an initial qualification step. Pump wear, elastomer compatibility, oxidation under recirculation, water contamination, filterability and long-duration component testing remain necessary before an industrial claim can be established.

Bearings

Journal bearings provide some of the strongest component-level palm evidence. Palm mid-olein has shown favorable hydrodynamic behavior in dedicated bearing rigs, and additive-treated palm mid-olein has subsequently demonstrated improved load-carrying and friction characteristics. These studies are important because they move beyond generic four-ball testing into pressure-field and film-behavior measurements relevant to rotating machinery [42,41].

Nevertheless, bearing qualification should include long-duration ageing and mixed-regime transitions. Start-up and shutdown can temporarily move a hydrodynamic bearing into boundary or mixed lubrication, where surface chemistry becomes more important. A commercial formulation therefore requires both bulk rheological performance and surface-protection capability.

Gears and Heavily Loaded Contacts

Gear lubrication presents severe contact pressures, sliding-rolling conditions and potential micropitting or scuffing. Native

vegetable oils may provide good lubricity but can require stronger anti-wear and extreme-pressure packages. Polyol esters and chemically modified palm derivatives are more promising than untreated triglycerides because molecular architecture can be optimized for viscosity and thermal stability. However, interaction with sulfur-, phosphorus- or other extreme-pressure chemistries must be evaluated without sacrificing biodegradability or material compatibility [25,8].

Nano-additives may provide supplementary surface protection, but gear systems also emphasize filterability and long-term dispersion. A particle size distribution acceptable in a short laboratory test could be unacceptable in industrial filtration. Consequently, the gear application is a strong example of why bench-scale friction improvements should not be equated with field readiness.

Metalworking and Forming

Vegetable oils are particularly attractive in metalworking because high polarity improves adsorption and lubrication at tool-workpiece interfaces. They may also reduce worker exposure to some components associated with conventional mineral-oil-based metalworking fluids. Bellini et al. Argued for vegetable-oil-based lubrication using a Triple Bottom Line perspective, linking technical performance to environmental and occupational dimensions [6]. Zhang et al. Further showed that nano-enhanced vegetable oils offer important opportunities for machining, although oxidation, extreme-pressure behavior and particle dispersion remain central considerations [44].

Palm mid-olein has been evaluated in cold forging, indicating an application pathway for palm fractions beyond conventional machine-oil use [43]. Future studies should integrate forming load, tool wear, surface finish, energy consumption and lubricant carry-over rather than relying only on friction measurements.

Refrigeration and compressor lubrication

Refrigeration highlights a different molecular constraint: miscibility with the refrigerant. Idrus et al. Studied palm-derived pentaerythritol esters with HFC R134a and showed that a base oil can possess otherwise attractive viscosity and pour-point properties yet suffer incomplete refrigerant miscibility because of molecular steric effects [18].

This application demonstrates the broader principle that lubricant qualification must include the working fluid or environment encountered in the actual machine. In refrigeration, oil return, heat transfer, refrigerant solubility, moisture sensitivity and chemical compatibility may dominate over the standalone tribological ranking of the base oil.

Agricultural and Open-Loss Machinery

Agricultural machinery is an intuitively attractive application because lubricant leakage can directly contaminate soil and water. Biodegradability can therefore create a clearer environmental benefit than in perfectly sealed systems. Yet agricultural machinery experiences dust, moisture, variable temperatures, high loads and long storage periods. Palm-derived hydraulic oils, chain lubricants and greases must consequently be validated under contamination and ageing conditions as well as tribological tests.

The 2025 TiO₂-palm-olein stability research is especially relevant here because the authors explicitly associated the formulation

pathway with agricultural machinery applications. Long-term dispersion stability becomes essential when machines remain idle for weeks or months between operating seasons [53].

Electric-Vehicle Drivetrains

Electric vehicles create a technologically exciting but demanding frontier. E-drivetrain fluids may need to lubricate gears and bearings while participating in heat management and operating near electrical windings, copper conductors, polymers and electronic systems. Electrical conductivity, dielectric behavior, copper compatibility, thermal management, foaming and material interactions may therefore be as important as friction and wear [54-56].

Nugroho et al. Reviewed nanoparticle-enriched palm-oil biolubricants in relation to electric-vehicle lubrication and reported promising reductions in friction and wear across the evidence assessed [57]. These results justify further investigation but should not yet be interpreted as full e-fluid qualification. Future palm-based EV fluids require standardized electrical-property measurements, copper corrosion testing, thermal ageing, elastomer compatibility, foaming analysis, and actual e-axle or transmission-component testing.

The difference among these applications can be summarized as a requirement matrix rather than a ranking of which industry is “best” for palm lubricants. The matrix makes explicit that hydraulic, bearing, gear, metalworking, refrigeration, agricultural, marine, and electric-drive applications impose different combinations of rheological, oxidative, anti-wear, compatibility, and dispersion-stability requirements.

Application	 VI / flow	 Oxidation	 AW / EP	 Compatibility	 Nano stability
 Hydraulics	High	High	High	High	High
 Journal bearings	High	High	Medium	Medium	Medium
 Gears	High	High	Very high	High	High
 Metalworking	Medium	High	Very high	Medium	High
 Refrigeration	High	High	Medium	Very high	Low/Medium
 Agricultural	High	High	High	High	High
 Marine/open loss	Medium	High	High	High	High
 EV drivetrains	High	Very high	High	Very high	Very high

Priority level: Very high High Medium Low/Medium

Source: Author synthesis. Compatibility includes relevant elastomers, metals, refrigerants, electrical materials or process fluids.

Figure 4: Application-specific qualification priorities

The matrix emphasizes that there is no universal palm biolubricant formulation. Application-specific engineering should therefore replace attempts to define one formulation as the generic optimum for all industrial machinery.

Discussion and Analysis

From Biodegradable Substitute to Performance-Designed Fluid The literature reviewed here indicates that the central scientific question has changed. Early biolubricant research often asked whether vegetable oils could replace mineral lubricants. Contemporary palm research increasingly asks how renewable carbon can be converted into molecules deliberately designed for industrial lubrication. The distinction is substantive. Substitution compares origins; engineering compares functions.

Native palm triglycerides already possess one important advantage: strong molecular polarity relative to hydrocarbon mineral oils. This can support boundary-film formation and effective lubricity. However, their disadvantages are equally structural. Unsaturated bonds contribute to oxidation sensitivity, while highly saturated fractions can present low-temperature constraints. The glycerol backbone introduces additional thermo-oxidative vulnerabilities. These problems cannot be solved by marketing biodegradability as a performance property; they require chemistry [9,10].

Polyol esterification, epoxidation, branching and estolide formation therefore represent different molecular solutions to different failure modes. TMP and pentaerythritol structures can improve thermal behavior and viscosity properties; epoxidation transforms vulnerable unsaturation and creates functionalization sites; branching can improve low-temperature behavior; and estolides can integrate branching with high viscosity index and lubricity. The rapid expansion of PFAD-derived ester chemistry is particularly important because it combines performance design with refinery-side-stream valorization [16,19,20].

Yet multi-property optimization remains essential. A lubricant molecule is not valuable because it maximizes one parameter. High viscosity can improve film thickness but increase pumping losses. Greater saturation may improve oxidation but harm cold flow. Increased polarity may improve adsorption but alter compatibility with other formulation components. Branching may reduce crystallization but affect biodegradation or synthesis cost. Nano-additives may decrease wear but create colloidal instability. The performance objective is therefore a constrained optimization problem.

The Palm-Biolubricant Performance Triangle

The evidence can be synthesized into a performance triangle with three interdependent objectives: **technical performance, environmental performance and commercial manufacturability**. A viable formulation must occupy an acceptable region in all three.

Technical performance includes friction, wear, viscosity-temperature behavior, oxidation life, low-temperature flow, thermal stability, corrosion protection and material compatibility. Environmental performance includes renewable content, biodegradability, toxicity, feedstock implications, production

energy, leakage impact and end-of-life behavior. Commercial manufacturability includes raw-material cost, catalyst productivity, purification requirements, batch consistency, additive availability, storage stability, standards compliance and OEM acceptance [7,4].

The triangle exposes an important sustainability risk: extensive chemical modification and elaborate additive systems can theoretically convert a vegetable oil into an excellent lubricant while progressively eroding its environmental or economic advantage. A multi-step synthesis requiring high temperatures, expensive catalysts, repeated vacuum distillation, solvent-intensive purification and difficult-to-recycle additives may be renewable in feedstock origin but less attractive on life-cycle or cost grounds. This is why future palm-biolubricant research should report process metrics alongside final fluid properties.

Biocatalysis illustrates this trade-off. Immobilized lipases can permit selective reactions under milder conditions and simplify purification, but enzyme manufacture and replacement, immobilization supports and reaction productivity influence commercial sustainability. Conversely, solid acid catalysts and non-catalytic high-temperature esterification may simplify catalyst removal but can increase energy demand. No pathway should therefore be labelled intrinsically “green” without system-level comparison [17,34].

PFAD as a Strategic Bridge Between Circularity and Performance

Among the reviewed palm feedstocks, PFAD offers an especially compelling research pathway because it can partially decouple industrial lubricant production from direct use of refined edible palm oil. Its high free-fatty-acid content eliminates some processing steps required when starting from intact triglycerides and creates opportunities for direct esterification.

PFAD-based NPG ester, 2-ethylhexyl ester, polyol esters and estolides demonstrate an increasingly sophisticated product hierarchy. The evolution from simple esterification toward structurally engineered estolide base oils suggests that refinery side-stream valorization can produce more than low-cost substitutes. In principle, PFAD can become a feedstock for high-value specialty oleochemicals [30,17,19,20].

Commercial attractiveness nevertheless depends on opportunity cost. PFAD already has competing uses; therefore, sustainability claims should compare alternative utilization pathways rather than assume that any PFAD valorization is automatically superior. Future life-cycle and techno-economic studies should include feedstock allocation, refinery integration, pretreatment, catalyst requirements, purification intensity and alternative PFAD markets.

Nano-Additives: A Performance Multiplier with an Evidence Deficit

Nano-additives provide some of the largest friction and wear improvements reported in emerging palm-lubricant studies, but they also expose one of the largest gaps between laboratory demonstrations and industrial evidence. Short-duration tribological tests are optimized for observing wear mechanisms; industrial lubrication requires stability over storage and long service intervals.

Three dimensions therefore require simultaneous study. First is tribological effectiveness, including friction reduction, wear suppression and tribofilm formation. Second is colloidal engineering, including particle aggregation, sedimentation, surface functionalization and dispersant selection. Third is system compatibility, including filtration, elastomers, pumps, seals, corrosion, environmental release and disposal [52,24,26].

The graphite-PKO study of Azman et al. is instructive because oleic acid did more than suspend a particle; it influenced graphite structural transformation and tribofilm development [23]. Similarly, TiO₂-palm-olein research demonstrates that ultrasonication history materially changes dispersion quality. These observations mean that “0.5 wt.% nanoparticle” is an inadequate formulation description unless dispersion history, particle-size distribution, surface treatment and stability are also reported.

Another underdeveloped question concerns end-of-life environmental behavior. Vegetable-oil biodegradability does not automatically make metal oxide, graphene, h-BN or other nanoscale additives biodegradable. Ecotoxicity, persistence, transformation and exposure pathways should therefore become part of the qualification framework. Bio-derived additives such as nanocellulose are potentially attractive in this respect, although their frictional effectiveness and storage behavior must still meet industrial requirements [50,51,58].

Why Laboratory Tribology Is Not Enough

The evidence base remains dominated by four-ball, pin-on-disc and related bench tests. These tests are essential for screening, but they simplify industrial systems. Real machines experience fluctuating loads, mixed materials, contamination, oxidation, start-stop cycles, vibration, changing temperatures and complex lubricant circulation. Consequently, the translation sequence should progress from bench testing to accelerated ageing, component rigs, pilot operation and field trials.

This observation is not a criticism of laboratory research; it identifies the next research stage. Component studies already exist for palm mid-olein journal bearings, roller chains and cold forging, providing models for future work [22,42,43,41]. More research should extend this logic to pumps, gearboxes, agricultural drivetrains, compressors and EV e-axes.

Ageing should be integrated throughout this sequence. Fresh-fluid qualification establishes baseline properties. Oxidized-fluid testing determines performance retention. Component tests establish whether degradation products, viscosity growth, acidity and additive depletion create operational problems. This “ageing-before-tribology” approach is more informative for commercial readiness than reporting only initial friction coefficients.

Proposed Technology-Readiness Framework

The reviewed evidence supports a staged framework for developing palm-derived lubricants. Each stage adds a distinct class of evidence needed to reduce technical uncertainty and prevent laboratory-scale performance from being mistaken for commercial readiness.

At **TRL 1-3**, research should establish molecular feasibility. Feedstock composition should be characterized; synthesis pathways optimized; product structures confirmed through appropriate analytical methods; and viscosity, thermal behavior, oxidation and initial tribology measured. Studies such as PFAD esterification and enzymatic palm-TMP synthesis principally occupy this proof-of-concept domain.

At **TRL3-4**, formulation engineering should optimize antioxidant packages, viscosity modifiers, pour-point depressants, anti-wear agents, corrosion inhibitors and nano-additive concentration. Mixtures should undergo storage and dispersion-stability evaluation rather than immediate tribological testing alone.

At **TRL 4-5**, standardized laboratory qualification becomes critical. Fresh and aged fluids should be benchmarked against commercial mineral, synthetic-ester and existing bio-based references. Relevant ASTM, ISO, DIN or application-specific methods should be selected for viscosity, oxidation, corrosion, foaming, demulsibility, wear, extreme pressure and low-temperature behavior.

At **TRL 5-6**, component-level validation should begin. A hydraulic formulation should run in pumps or hydraulic rigs; a bearing lubricant should undergo extended bearing tests; a gear oil should be evaluated under gear-specific load and fatigue conditions; and an e-fluid should undergo electrical, copper and drivetrain-relevant tests.

At **TRL 6-7**, pilot and field demonstrations should investigate service interval, oil-condition monitoring, contamination tolerance, maintenance implications, lubricant consumption and compatibility with existing filtration and sealing systems. These demonstrations should establish whether laboratory gains persist under realistic duty cycles, contamination, maintenance practices, and filtration conditions.

At **TRL8-9**, industrial commercialization requires manufacturing reproducibility, supply reliability, regulatory compliance, full standards certification where applicable, OEM approval, cost competitiveness, life-cycle assessment, and market-specific value propositions. At this stage, repeatable manufacturing quality and a defensible value proposition become as important as further incremental improvements in bench-scale tribology.

The proposed progression is shown in Figure 5. Importantly, moving to a higher TRL should require evidence from the previous level rather than isolated demonstration of one attractive property.

This framework also prevents premature commercialization claims. Laboratory synthesis may demonstrate scientific feasibility, but industrial readiness requires cumulative evidence that the fluid remains technically effective, environmentally defensible and economically manufacturable.

Research Gaps and Future Agenda

A first priority is development of **harmonized benchmark protocols**. Studies frequently use different contact geometries, loads, temperatures, speeds and commercial reference oils,

making cross-study comparison difficult. Palm-biobased formulations should increasingly be compared against standardized mineral and synthetic benchmarks of equivalent viscosity grades, with full reporting of test conditions.



Figure 5: Technology-readiness roadmap for palm-based industrial biolubricants

Second, **feedstock composition should be reported as a design variable**. Palm fractions vary with processing history and fatty-acid composition. Studies should report detailed composition rather than using labels such as “palm oil” without sufficient characterization. This is particularly important where saturation influences rheology or oxidation.

Third, research should integrate **oxidative ageing and tribological performance**. Oxidation-induction tests alone do not indicate whether an aged fluid can still protect a component. Future protocols should oxidize formulations to defined endpoints before repeating friction, wear, corrosion and deposit tests.

Fourth, **hydrolytic stability and water contamination** require more attention. Industrial machinery commonly encounters moisture through condensation, leakage or processing environments. Ester hydrolysis can generate acids and alter corrosion behavior. Water may also modify nanoparticle dispersion and additive performance.

Fifth, nano-biolubricant research requires a **minimum dispersion-reporting standard** covering particle chemistry, primary size, agglomerate distribution, surface modification, dispersant identity, mixing energy, ultrasonication time, zeta potential or equivalent stability indicators, sedimentation duration, viscosity change and filtration behavior. Without this information, tribological results are difficult to reproduce or translate.

Sixth, nanoparticle environmental safety should be integrated with green tribology. A lubricant should not be called environmentally benign based solely on vegetable-oil content if its nano-additive fate is unknown. Biogenic and cellulose-based nanomaterials deserve more attention where they can achieve adequate tribological performance [50,28].

Seventh, more **component-level and field evidence** is essential. Palm mid-olein journal-bearing and roller-chain experiments provide useful precedents, but equivalent work is needed for hydraulic pumps, gears, agricultural transmissions, marine systems, compressors and e-drive components.

Eighth, electric-vehicle applications require a broader definition of lubricant performance. Friction reduction should be evaluated alongside thermal conductivity, specific heat, electrical conductivity, dielectric breakdown, copper corrosion, polymer compatibility, foaming and long-term oxidation. Nanoparticle selection becomes especially complex because particles introduced for tribological purposes can also change electrical behavior.

Ninth, techno-economic analysis should become standard for advanced molecular routes. Estolides, multi-step polyol esters and enzymatic processes may achieve excellent properties but remain constrained by feedstock purification, catalyst costs, reaction time, vacuum requirements or downstream separation. TEA can identify which experimental improvements would most strongly reduce manufacturing cost [59].

Finally, palm-biolubricant sustainability assessment requires **comparative LCA rather than renewable-content assumptions**. Important variables include plantation and refinery allocation, side-stream credits, processing energy, catalyst and solvent footprints, lubricant lifetime, leakage rates, frictional energy savings, component-life extension and end-of-life treatment. PFAD-based products may perform particularly well when side-stream allocation and avoided waste treatment are relevant, but the result should be demonstrated quantitatively.

Conclusion

Palm-derived oils have progressed beyond the stage at which they can be assessed simply as biodegradable alternatives to petroleum lubricants. The contemporary evidence demonstrates a transition toward **performance-engineered oleochemical fluids** in which fatty-acid composition, ester architecture, branching, epoxidation, polyol structures, estolides, antioxidant systems, and nanoscale additives are deliberately manipulated to achieve application-specific lubrication behavior.

The strongest evidence supports several conclusions. Native palm fractions can provide favorable lubricity, but no single palm feedstock is universally optimal. Chemical modification is necessary when the application demands improved oxidation resistance, low-temperature performance, viscosity control, or thermal durability. PFAD has emerged as a strategically important circular feedstock for high-value ester and estolide base oils. Nano-additives can substantially enhance friction and wear performance, but their commercialization depends on solving dispersion, filtration, compatibility, and environmental-

safety problems. Component studies in bearings, roller chains, and forming operations demonstrate that translation beyond conventional tribometers is achievable, while hydraulic, refrigeration, and emerging electric-drive applications reveal the importance of application-specific qualification.

The central conclusion is therefore that the future of palm-based biolubricants does not depend on proving that palm oil “can lubricate.” That question has largely been answered. The more important challenge is identifying **which palm-derived molecular architecture, formulation, and additive system provides the optimum balance of lubricity, durability, stability, compatibility, environmental performance, and cost for a defined machine and duty cycle.**

Commercial development should consequently follow a molecule-to-market pathway: feedstock characterization, molecular engineering, formulation optimization, standardized fresh-fluid testing, accelerated ageing, component validation, field trials, standards compliance, techno-economic assessment, life-cycle analysis and OEM qualification. When these steps are treated as an integrated engineering process, palm-derived lubricants can move from environmentally motivated substitutes toward technically competitive specialty fluids capable of contributing simultaneously to green tribology, circular oleo chemistry and sustainable industrial machinery.

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