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From Molecular Structure to Grid-Scale Qualification: Palm-Oil-Derived Natural Ester Transformer Fluids for Next-Generation Power Systems—A Critical Review

Loso Judijanto

IPOSS Jakarta, Indonesia

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Abstract

The decarbonization and expansion of electricity systems are increasing demand for transformer technologies that combine reliability, fire safety, environmental compatibility, and long service life. Palm-oil-derived natural esters represent a potentially important class of renewable dielectric and cooling fluids, particularly for countries with established palm-based oleochemical industries. This critical qualitative literature review evaluates whether palm-derived esters can progress from promising laboratory insulating liquids to dependable grid-scale transformer fluids. Rather than treating transformer-fluid suitability as a simple comparison of individual properties, the review develops a structure–property–performance–qualification framework linking fatty-acid composition, molecular architecture, refining and modification to dielectric behavior, thermal management, moisture partitioning, cellulose ageing, oxidation, dissolved-gas behavior, material compatibility, transformer design, and qualification. Evidence indicates that palm oil, palm olein, palm-fatty-acid esters, and palm-kernel-oil methyl esters can provide high dielectric strength, favorable fire safety, and useful moisture-management characteristics. However, higher viscosity, oxidation susceptibility, dielectric loss, ageing-dependent changes, and uncertainty in ester-specific diagnostics remain important limitations. Chemical modification, blending, antioxidants, nanoparticle engineering, and molecular design can alleviate several constraints, but laboratory enhancement is not equivalent to fleet reliability. The review therefore proposes a staged Palm-Ester Grid Qualification Ladder encompassing molecular specification, standardized fluid tests, multistress ageing, material compatibility, full-transformer validation, field demonstration, and fleet-scale evidence. Palm-derived esters appear technically credible, but dependable grid deployment requires fluid-specific transformer engineering rather than simple substitution for mineral oil.

***Corresponding author**: Loso Judijanto, IPOSS Jakarta, Indonesia.

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Introduction

Power transformers are indispensable assets in electricity generation, transmission, distribution, renewable-energy integration, industrial electrification, and increasingly complex smart-grid systems. Their reliability depends substantially on the performance of their internal insulation system, in which the liquid dielectric performs two inseparable functions: electrical insulation and transfer of heat generated by the magnetic core and windings. Petroleum-derived mineral oil has historically performed these functions effectively because of its relatively low viscosity, established dielectric performance, extensive diagnostic knowledge base, widespread availability, and accumulated operating experience. Its continued dominance, however, increasingly conflicts with requirements for improved fire safety, environmental protection, biodegradability, renewable material sourcing, and lower dependence on petroleum-derived materials [1-4].

Natural esters derived from vegetable feedstocks have therefore moved from an experimental curiosity toward a commercially relevant class of transformer insulating liquids. Their principal advantages include high flash and fire points, rapid biodegradability, renewable origins, comparatively high moisture solubility, and favorable interaction with cellulose insulation. Yet natural esters cannot be evaluated merely as "green mineral oil." Their triglyceride or ester molecular architecture differs fundamentally from hydrocarbon-based mineral oil, producing different viscosity, polarity, permittivity, oxidation pathways, hydrolysis behavior, moisture equilibrium, heat-transfer behavior, streamer characteristics, and ageing products. These differences are precisely why some properties are attractive while others complicate direct substitution [3,5-8]. Recent thermo-chemical and dielectric characterization of a bio-based natural ester further supports the need to evaluate electrical and thermal performance jointly rather than treating biodegradability alone as evidence of transformer readiness [8].

Palm-derived dielectric liquids deserve separate attention within this broader natural-ester category. The term encompasses chemically different materials, including refined palm oil, palm olein, palm-derived triglycerides, palm fatty-acid esters (PFAE), and palm-kernel-oil methyl esters (PKOME). These materials differ substantially in chain length, saturation, molecular size, polarity, viscosity, oxidation susceptibility, and low-temperature behavior. Experimental investigations have shown that processed palm-derived liquids may achieve useful breakdown voltages and high flash points, while drying and esterification can alter their performance markedly. Consequently, the technologically relevant question is not whether "palm oil" in a generic sense possesses sufficient dielectric strength, but which palm-derived molecular architectures and formulations are suited to which transformer duty classes [9-11].

Palm-based fluids are especially relevant to Southeast Asian power systems. Indonesia and Malaysia possess large palm-oil and oleochemical industries, while their electricity systems are simultaneously expanding renewable generation, distribution infrastructure, data-intensive loads, electrified transportation, and environmentally sensitive transmission networks. A technically qualified palm-based transformer fluid could therefore create value beyond commodity palm-oil markets by linking oleochemistry to advanced electrical equipment. However, localization of feedstock does not remove the engineering requirements imposed on transformer insulation. Transformer operators require repeatable feedstock specifications, controlled oxidation behavior, predictable dielectric failure probabilities, reliable cooling, compatibility with paper and construction materials, validated dissolved-gas interpretation, and operational evidence extending far beyond short laboratory tests.

The existing literature contains an apparent paradox. On the one hand, palm-derived oils and esters often demonstrate attractive breakdown strength, moisture handling, flash/fire points, and potential environmental benefits. On the other hand, transformer-scale investigations of natural esters repeatedly show that higher viscosity can modify fluid circulation and increase winding temperatures compared with mineral oil. In identical-transformer experiments, the cellulose-ageing advantage of natural ester was reduced when higher winding temperatures resulting from poorer heat dissipation were considered. Thus, a liquid that appears superior in a laboratory ageing vessel maintained at identical temperature may not automatically produce a superior transformer when thermal-hydraulic effects change the actual operating temperature [12-14].

The same caution applies to dielectric measurements. High power-frequency breakdown voltage is essential but does not independently establish suitability for high-voltage equipment. Lightning impulse breakdown, streamer propagation, partial-discharge inception, space-charge accumulation, dielectric loss, moisture transients, long oil-gap behavior, and electric-field redistribution at oil–paper interfaces may reveal limitations that are not visible in routine AC breakdown testing. Recent work is particularly significant because modified palm fatty-acid ester has shown strong negative lightning-impulse performance in long oil gaps relative to soybean natural ester, demonstrating that deliberate molecular modification may create transformer-relevant advantages rather than merely reproducing conventional vegetable-oil characteristics [15].

Accordingly, this review addresses a translational engineering gap. Previous reviews have comprehensively examined vegetable oils, ester fluids, nanofluids, and transformer standards [1,3,4,6,16]. The present study instead organizes the evidence around a structure–property–performance–qualification chain, using palm-derived fluids as the principal case while treating other natural esters as comparative engineering evidence. The overarching research question is: What engineering conditions are necessary for palm-oil-derived natural esters to become dependable grid-scale dielectric and cooling fluids?

More specifically, the review asks how palm molecular composition affects electrical, physicochemical, thermal, and oxidative properties; how palm-derived esters perform under AC, DC, impulse, partial-discharge, moisture, and ageing stresses; whether cellulose-life benefits outweigh transformer-scale thermal penalties; how oxidation and hydrolysis alter long-term performance; whether existing diagnostics can be transferred from mineral oil; which chemical and nanoengineering strategies best address remaining deficiencies; and what sequence of validation is needed to move a formulation from laboratory testing to utility deployment. The principal contribution is therefore a Palm-Ester Structure–Property–Performance–Qualification (SPPQ) Framework and an associated Palm-Ester Grid Qualification Ladder.

Literature Review: Conceptual and Theoretical Foundations

Transformer Liquid Insulation as a Coupled Electro-Thermal System

Transformer liquids cannot be meaningfully evaluated by one parameter because transformer failure mechanisms are coupled. Electrically, the liquid must suppress charge transport, streamer development, partial discharges, and bulk breakdown under alternating-current (AC), direct-current (DC), and impulse voltage stresses. Thermally, it must remove core and winding losses through conduction and convection. Chemically, it must remain sufficiently stable over decades of exposure to temperature, oxygen, metals, cellulose, moisture, and electrical discharges. Mechanically and materially, it must impregnate porous insulation and remain compatible with pressboard, copper, coatings, seals, and elastomers [2,7].

Breakdown in insulating liquids is stochastic rather than deterministic. Water, particles, bubbles, electrode geometry, electric-field nonuniformity, temperature, ageing products, molecular ionization potential, and charge mobility all influence the probability and pathway of breakdown. This is why studies commonly complement mean breakdown voltages with Weibull failure analysis and why results obtained with small electrode gaps should not automatically be extrapolated to large high-voltage insulation structures. Molecular-level studies increasingly connect macroscopic breakdown to ionization energy, electron affinity, excitation energy, free volume, hydrogen bonding, and molecular mobility [17-19].

The thermal function is equally important. Heat generated in the windings and core is transported through solid insulation and circulating liquid toward the tank and cooling system. Natural convection depends strongly on viscosity and density differences, while thermal conductivity and specific heat influence heat transport. Because viscosity decreases with temperature, the relative cooling disadvantage of an ester is neither constant nor adequately described by a room-temperature property value. Computational and transformer-scale studies therefore provide stronger engineering evidence than fluid-only thermal-conductivity measurements [12-14].

Natural-Ester Chemistry and the Importance of Molecular Architecture

Natural ester liquids are commonly based on triglycerides in which three fatty-acid chains are esterified to a glycerol backbone. Their behavior depends on chain length, branching, degree of unsaturation, molecular size, and intermolecular interactions. Unsaturated bonds generally improve low-temperature fluidity but provide chemically reactive sites susceptible to oxidation. Increased saturation can improve oxidative resistance but may increase pour point and crystallization tendency. Large triglyceride structures also contribute to higher viscosity than that of conventional transformer mineral oils [3,20, 21].

This trade-off is especially important for palm materials because palm feedstocks contain significant saturated and monounsaturated fatty-acid fractions. Palm oil, palm olein, palm kernel oil and their converted esters cannot therefore be treated as one material category. Palm fatty-acid esters and palm-kernel methyl esters can possess substantially lower molecular size and viscosity than their original triglyceride oils. Mohd et al., demonstrated clear effects of hydrocarbon-chain type, chain length, and molecular size on electrical and physicochemical characteristics of palm-derived products [9]. Chen et al., similarly showed that incorporating PFAE into a rapeseed-based natural ester substantially lowered kinematic viscosity, although the molecular characteristics of PFAE introduced an oxidation-stability trade-off [22].

The growing literature on modified esters therefore implies a shift in research philosophy. The objective should not be to identify a naturally occurring vegetable oil that happens to reproduce all mineral-oil properties. Instead, feedstock chemistry can be viewed as a molecular design space in which chain length, ester core, branching, unsaturation, additives, and blending ratios are engineered toward target properties. Molecular-dynamics work now predicts pour-point behavior from fractional free volume and molecular mobility, while generative machine-learning approaches have begun screening thousands of candidate ester structures for lower viscosity and appropriate dielectric electronic properties [21,23].

Moisture, Cellulose and Ageing Theory

The conventional mineral-oil transformer is fundamentally an oil–cellulose insulation system. Cellulose ageing is accelerated by temperature, moisture, oxygen, and acids, while loss of degree of polymerization eventually produces mechanical embrittlement. Natural esters alter this process because their higher polarity enables them to dissolve substantially more water than mineral oils. Consequently, moisture equilibrium shifts from the cellulose toward the liquid phase, potentially reducing the moisture content of paper and slowing hydrolytic cellulose degradation [24,25].

That effect is potentially valuable, but it should not be summarized simply as "natural esters tolerate more moisture." Absolute water concentration, relative saturation, water activity, temperature, and transient redistribution all matter. During cooling, water partitioning changes and local conditions can temporarily reduce partial-discharge inception voltage. Jiang, Du and Cavallini [26] demonstrated that moisture migration during cooling can generate transient periods of elevated surface-discharge risk in ester oil–pressboard insulation. A moisture-management advantage therefore coexists with dynamic electrical risks and requires condition assessment based on ester-specific moisture equilibrium rather than mineral-oil thresholds [26,24].

Oxidation, Hydrolysis and Diagnostic Interpretation

The unsaturated molecular structures of natural esters make oxidative degradation a major engineering issue. Oxidation may generate hydroperoxides, acids and higher-molecular-weight products, increasing viscosity and potentially progressing toward polymerization or gelling when exposure to oxygen is severe. The degradation pattern differs from mineral oil, where oxidation is strongly associated with sludge formation. Accelerated open-beaker studies show that natural-ester gelling is a credible concern when preservation systems fail or prolonged exposure to atmospheric oxygen occurs [27,28].

Hydrolysis introduces another pathway because the ester bond can react with water, while temperature and acidity influence reaction kinetics. These mechanisms change not only bulk-fluid properties but also dissolved-gas signatures. Palm-oil molecular simulations have identified temperature-dependent pyrolysis pathways for major triglycerides, and moisture can alter those pathways. Consequently, dissolved-gas analysis developed around mineral-oil fault chemistry cannot always be transferred unchanged to ester-filled transformers [29-31].

Figure 1 illustrates that palm-derived transformer-fluid suitability cannot be inferred from feedstock identity or breakdown voltage alone. The fluid passes through several coupled transformation and validation layers before it becomes a grid asset.

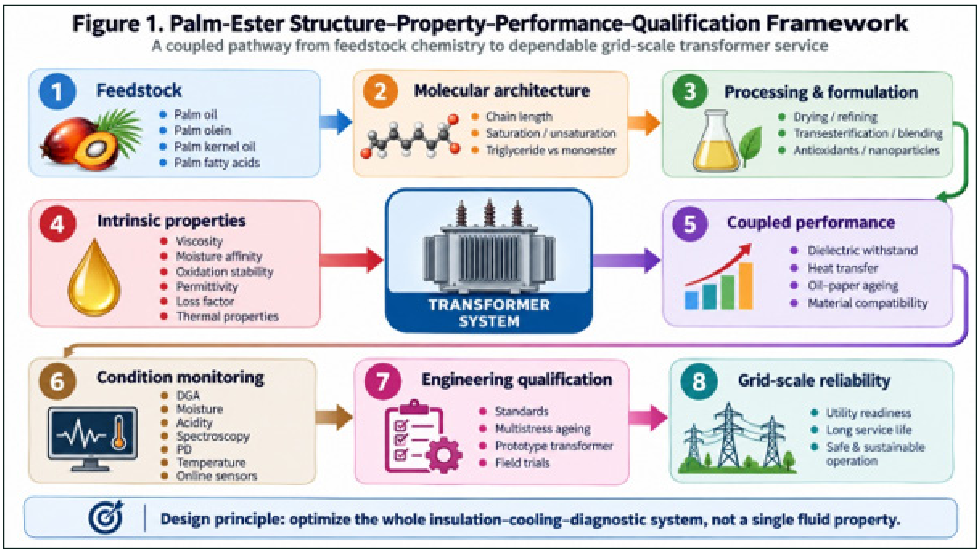

Figure 1: Palm-Ester Structure-Property-Performance-Qualification Framework.

Figure. 1 shows that the framework also explains why conflicting conclusions appear in the literature. A modification may improve one layer while worsening another. For example, reducing molecular size can lower viscosity, but changing molecular architecture may simultaneously affect oxidation and discharge behavior. Nanoparticles can increase breakdown voltage or thermal conductivity yet introduce long-term dispersion and sedimentation questions. Grid qualification therefore requires optimization across the complete chain rather than maximization of any isolated property.

Method

This study employs a critical qualitative literature review rather than a systematic literature review or meta-analysis. The qualitative approach was selected because the available evidence is highly heterogeneous in fluid composition, transformer geometry, test voltage, electrode spacing, moisture conditioning, accelerated-ageing procedure, temperature, oxygen exposure, nanomaterial concentration, paper type, statistical treatment, and scale of experimentation. A numerical aggregation of such results without sufficiently controlling these contextual differences could produce misleading comparisons.The literature synthesis concentrates primarily on peer-reviewed journal articles published between 2020 and 2026. Earlier foundational concepts are acknowledged where necessary for interpretation, but the reference base used for substantive synthesis is dominated by contemporary evidence. Literature was identified around combinations of terms concerning natural ester, palm oil, palm olein, palm fatty acid ester, palm kernel oil methyl ester, transformer insulation, breakdown voltage, lightning impulse, partial discharge, thermal ageing, cellulose, moisture, oxidation, dissolved gas analysis, nanofluid, thermal management, and retrofilling. The evidence base was developed from electrical-engineering, energy, materials, dielectric, and molecular-science journals indexed or distributed through major scholarly and publisher platforms.

The literature was interpreted through thematic coding rather than through PRISMA-style screening or quantitative study weighting. Six primary evidence domains were defined: (1) molecular structure and fluid formulation; (2) dielectric behavior; (3) thermal and hydraulic behavior; (4) moisture, oil–paper interaction and ageing; (5) oxidation and diagnostics; and (6) modification, qualification, and scale-up. Palm-specific studies received particular interpretive weight. Evidence derived from soybean, rapeseed, canola, sunflower, and commercial natural esters was incorporated when it addressed mechanisms or transformer-engineering problems transferable to palm-derived formulations.

Comparisons were treated cautiously. "Natural ester" is not considered a chemically uniform intervention. Similarly, data obtained from unprocessed crude palm oil, refined palm olein, PFAE, PKOME and commercial modified natural esters were not merged as though they represented identical fluids. The synthesis instead asks what specific molecular or formulation characteristic explains a reported result. This approach follows the structure–property reasoning emerging from recent molecular, experimental and review literature [22,19,7,21].

Evidence was also classified conceptually by technology maturity. Molecular simulations and bench-scale fluid tests were interpreted as mechanistic or proof-of-concept evidence; sealed-vessel oil–paper ageing and multistress dielectric experiments represented insulation-system evidence; computational fluid dynamics (CFD) and full-transformer temperature-rise studies were treated as equipment-level evidence; and long-duration operating or retrofill investigations were treated as translational evidence. This hierarchy prevents short-duration laboratory results from being presented as equivalent to grid-scale validation.

Results: Thematic Findings

Palm Feedstock Chemistry Determines the Feasible Performance Envelope

The strongest consistent finding is that the performance of palm-derived insulating fluids is controlled by molecular composition rather than the botanical label "palm." Mohd et al [9] evaluated triglyceride oils, fatty acids, fatty esters and glycerol derived from palm feedstocks and demonstrated substantial variation in viscosity, flash point, moisture and dielectric breakdown. Drying refined-bleached-deodorized palm olein substantially reduced water content and increased dielectric strength, illustrating that apparent feedstock performance can be dominated by fluid preparation. Muangpratoom et al likewise observed pronounced differences among six crude palm-oil products, including differences in dielectric loss, permittivity, acidity, moisture and impulse behavior [11]. These studies indicate that transformer-fluid qualification must define a chemical product specification rather than merely state "palm oil" as the feedstock [9,11].

The fatty-acid pattern generates several opposing effects. Increasing unsaturation generally improves fluidity because cis double bonds disrupt molecular packing, but the same double bonds create sites susceptible to autoxidation. More highly saturated structures may resist oxidative attack but can exhibit poorer low-temperature mobility. Chain length, branching and ester core similarly affect free volume and intermolecular friction. Recent molecular-dynamics studies show that shorter fatty-acid chains and branching can lower predicted pour point, while the relationship between unsaturation and low-temperature behavior can be interpreted through mean-square displacement and fractional free volume [20,21].

Palm fatty-acid esters are therefore particularly interesting. Chen et al., modelled blends of rapeseed natural ester and PFAE and reported substantial reductions in viscosity as PFAE was introduced, while also identifying an oxidation-stability penalty associated with the PFAE molecular structure [22]. Ye et al., however, found that a low-viscosity modified PFAE exhibited strong negative lightning-impulse breakdown behavior relative to soybean natural ester in large electrode gaps [15]. Taken together, these findings indicate that palm-derived monoesters and short-chain formulations may overcome one of the most persistent disadvantages of conventional triglyceride natural esters, but their formulation must be optimized simultaneously for oxidation stability and dielectric performance [22, 15].

Palm kernel derivatives add another dimension. Oparanti, Khaleed and Abdelmalik demonstrated that palm-kernel-oil-based ester fluids can serve as bases for dielectric nanofluids, while Kamhoua et al., combined experiments and COMSOL simulations to examine PKOME as a transformer cooling and insulating medium [32,33]. More recently, Boyekong et al., investigated thermally upgraded Kraft (TUK) and Nomex-910 papers impregnated with PKOME during thermal ageing, demonstrating that monoester–paper systems merit consideration as integrated insulation systems rather than solely as liquid substitutes [34].

Figure. 2 highlights that there is no chemically inevitable "best" palm ester. Molecular design involves balancing oxidation resistance, low-temperature fluidity, viscosity, flash/fire behavior, dielectric characteristics, and interaction with cellulose.

Figure. 2 explains that palm-derived transformer-fluid development should therefore move toward target-property formulation. Molecular composition, antioxidants, blending, and transesterification should be selected together. The recent emergence of machine-learning-based molecular screening reinforces this direction because ester candidates can increasingly be designed computationally before laboratory synthesis [23].

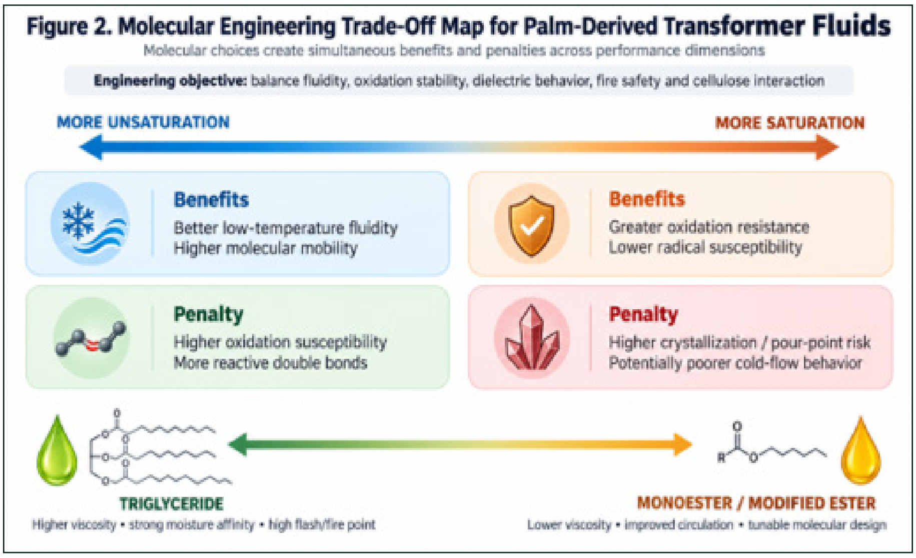

Figure 2: Molecular Engineering Trade-Off Map for Palm-Derived Transformer Fluids.

Dielectric Performance is Promising, but Ac Breakdown Voltage is an Incomplete Qualification Metric

Palm oils can display high AC breakdown strength when adequately processed. Hamid et al., found that palm oil provided competitive AC breakdown performance relative to mineral oil, although dielectric dissipation and resistivity varied by oil type [10]. Muangpratoom et al., similarly identified promising AC and positive lightning-impulse characteristics in specific palm-oil samples [11]. These findings support technical feasibility but also reveal that high dissipation factors in some palm oils may offset apparently strong breakdown performance [10,11].

Breakdown voltage also varies with temperature and molecular structure. Ye et al., reported non-monotonic low-temperature breakdown behavior in soybean- and palm-based natural esters between −20°C and 20°C [17]. Molecular simulation connected the trend with viscosity, interaction energy, water association, hydrogen bonding, free volume and electronic characteristics. Such evidence is important because it demonstrates that a transformer fluid does not possess one immutable "breakdown voltage"; the probability of failure is conditional on temperature, moisture state, geometry and molecular mobility [17].

Lightning impulse is especially important for higher-voltage deployment. Natural esters have historically generated concern because their streamer behavior under negative impulse can differ from mineral oil. Density functional theory (DFT) investigations show that ionization potential, dipole moment, excitation behavior and charge transport help explain these differences [18]. Numerical streamer modelling has further demonstrated that discharge propagation is sensitive to molecular and electrohydrodynamic properties [35]. Modified esters may provide a pathway forward: Ye et al., connected altered molecular microparameters with impulse behavior, and Ye et al., reported that PFAE outperformed soybean natural ester increasingly as the oil gap was extended, with a particularly large advantage at a 105-mm gap [15,19]. This result directly supports the possibility that palm-based molecular modification can contribute to higher-voltage transformer applications rather than only distribution-class use [18,35,19,15].

The evidence base is also expanding toward DC and high-voltage direct-current (HVDC) applications. Zou et al., found that thermally upgraded paper aged in natural ester could exhibit higher resistivity and DC breakdown voltage than comparable mineral-oil-impregnated paper [36]. Yoon, Chen and Hosier and Yoon, Hosier and Chen subsequently showed that ageing and moisture alter space-charge accumulation in natural-ester-impregnated paper, but strong DC breakdown performance can persist [25,37]. Kanumuri et al., further examined how thermal ageing influences DC conductivity and breakdown of natural ester for HVDC applications [38]. Collectively, these studies demonstrate that ester qualification must include the solid insulation and space-charge behavior, not merely liquid breakdown [36,37,25, 38].

Partial discharge (PD) provides another qualification layer. Amalanathan et al., found that thermal ageing altered PD inception and breakdown behavior in natural ester across several voltage stresses, while their companion investigation of aged ester-impregnated pressboard demonstrated sensitivity to AC, DC polarity, harmonics and ripple [39]. Sangineni, Chandrasekaran and Nayak further showed that oxidative ageing changes partial-discharge characteristics in mineral–natural-ester blends [40]. Such findings imply that ester-filled transformer diagnostics and insulation coordination should incorporate ageing-dependent discharge behavior rather than relying on fresh-fluid tests alone [39-42]. Recent comparative testing across vegetable-based natural esters also found meaningful fluid-to-fluid differences in partial-discharge inception voltage and phase-resolved patterns, reinforcing the need for formulation-specific PD qualification [42].

Microbubbles are an emerging concern. Zeng et al showed through electrohydrodynamic modelling that bubble position and distribution can materially influence streamer inception, branching and propagation in natural ester [43]. This is relevant to high-loading, high-field transformers because electrothermal stress and fluid degradation can generate gas phases whose effects are not captured by routine breakdown tests. Advanced qualification should therefore include bubble-mediated discharge, long-gap streamer propagation and repeated impulse exposure, especially before extrapolating laboratory results to large power-transformer geometries [43].

Thermal Management Remains One of the Most Important Barriers to Direct Substitution

Natural esters may possess useful thermal conductivity and heat capacity, but the engineering bottleneck is often viscosity. Increased viscosity reduces fluid velocity in winding cooling ducts, alters boundary-layer behavior and can increase winding and top-oil temperatures. Cilliyuz et al., demonstrated this directly with identical transformer units filled with different insulating liquids [12]. The natural-ester transformer showed poorer heat dissipation, and although the ester remained beneficial for paper ageing, part of that advantage was consumed by higher operating temperature. This finding is critical because it exposes a limitation in accelerated ageing comparisons performed at externally imposed equal temperatures.

Multiphysics models reach similar conclusions. Garelli et al., conducted coupled electromagnetic, thermal and fluid simulations of an oil-natural-air-natural (ONAN) transformer and reported lower average flow velocities and higher temperatures when a biodegradable ester was used rather than mineral oil [13]. Transformer cooling is therefore not determined by thermal conductivity in isolation; density, viscosity, heat capacity, geometry and natural-convection driving forces interact. Nadolny similarly emphasized the need to assess both the bulk liquid and the thermal properties of paper–oil insulation when judging transformer thermal performance [13,14]. Recent IEEE Access modelling likewise showed that a mineral-oil-oriented thermal standard can materially misestimate top-oil temperature for natural-ester-filled underground transformers unless the thermal model is adapted to the fluid-specific behavior [44].

Palm-derived monoesters provide a potentially important solution because they can achieve much lower viscosity than conventional triglyceride natural esters. Kamhoua et al., obtained close agreement between measured and simulated temperature distributions for a PKOME-based transformer system [33]. Although such evidence is not yet equivalent to large-fleet service history, it demonstrates that palm-derived molecular conversion can directly address the thermal-hydraulic limitation that otherwise weakens the natural-ester value proposition. Chen et al., similarly showed that PFAE blending can sharply reduce the viscosity of mixed natural ester [22].

The correct engineering strategy may therefore differ between new transformers and retrofits. A new transformer can be designed around ester properties by changing cooling-duct dimensions, radiator area, fluid flow, winding arrangement, permissible thermal class or loading strategy. A mineral-oil transformer that is retrofilled with ester retains geometry optimized for a lower-viscosity liquid. Retrofilling must consequently be evaluated by temperature-rise tests and field distribution rather than by fluid compatibility alone. Montero, García and Burgos showed that changing to natural ester alters electric-field distribution because of differences in permittivity and residual mineral-oil impregnation of the solid insulation [45]. Karaman et al., likewise demonstrated measurable changes in dielectric properties and viscosity in natural-ester/mineral-oil mixtures relevant to retrofilling [45,46].

Moisture Affinity is A System-Level Advantage Only when Dynamic Behavior is Controlled

One of the strongest arguments for natural ester is its ability to absorb more water than mineral oil at comparable conditions. Because cellulose deterioration is strongly moisture-dependent, transfer of water from paper to ester can reduce paper moisture and contribute to longer mechanical life. Villarroel et al., demonstrated through experimental data and modelling that moisture dynamics in natural-ester-filled transformers differ fundamentally from mineral-oil systems and should be integrated into dynamic loading and asset-management decisions [24].

The benefit, however, depends on how moisture is expressed. A high concentration of dissolved water in ester does not necessarily imply the same electrical risk as the same absolute concentration in mineral oil because saturation limits differ substantially. Water activity and relative saturation are more meaningful for assessing risk. Furthermore, rapid temperature changes redistribute water between cellulose and fluid. Jiang, Du and Cavallini showed that cooling transients could produce temporary reductions in PD inception voltage in both ester and mineral-oil systems [26]. Thus, natural esters can simultaneously reduce long-term cellulose moisture and create distinct short-term electrical conditions during dynamic operation.

Yoon, Hosier and Chen extended this issue to multilayer natural-ester-impregnated paper under DC stress [25]. The polar ester system extracted moisture differently from paper and displayed distinct charge accumulation while retaining favorable DC breakdown behavior. The practical implication is that ester-filled transformers need moisture interpretation charts, sensors and alarm thresholds adapted to ester chemistry. A utility that retrofills an asset but continues interpreting water concentration using mineral-oil rules may misdiagnose the insulation state.

Figure. 3 explains why the statement “natural esters tolerate water” is incomplete. Moisture behavior is dynamic and linked to both ageing and electrical risk.

Figure. 3 explains that over long periods, greater ester moisture solubility can be beneficial because it reduces moisture retained in cellulose. During temperature transients, however, equilibrium shifts continuously. Therefore, the relevant variable for transformer management is not a single ppm value but the coupled evolution of temperature, relative saturation, paper moisture and electrical stress.

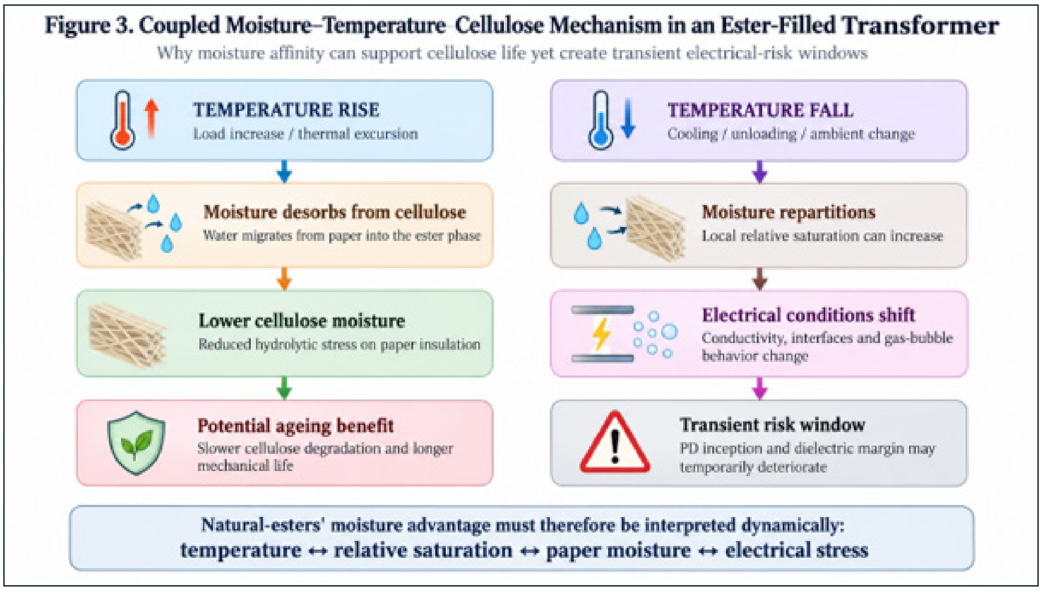

Figure 3: Coupled Moisture-Temperature-Cellulose Mechanism in an Ester-Filled Transformer.

Cellulose Ageing is a Genuine Advantage, but Whole-Transformer Temperatures Determine its Magnitude

Laboratory ageing evidence generally supports slower cellulose deterioration in natural ester than in mineral oil under comparable conditions. Natural esters can reduce paper moisture and their relatively high-molecular-weight acids may be less aggressive toward cellulose than low-molecular-weight acids generated in mineral-oil systems. However, this advantage is conditional rather than absolute. Amalanathan et al showed that thermal ageing alters the surface-discharge and trap characteristics of ester-impregnated pressboard, while Yoon, Chen and Hosier found that ageing can increase acidity and charge accumulation even as DC breakdown performance remains strong [37,41].

Palm-specific evidence is beginning to close an important gap. Boyekong et al compared thermally upgraded Kraft and Nomex-910 papers impregnated with PKOME, monitoring dielectric and physicochemical behaviour during ageing [34]. The study demonstrates the feasibility of natural monoester–paper systems but also shows that fluid viscosity and acidity evolve during ageing. Oparanti, Fofana and Jafari formulated a low-viscosity natural ester incorporating palm-kernel methyl ester and antioxidants, reporting improved thermo-oxidative behavior and compatibility with Kraft paper [47]. Together, these studies indicate that palm-derived monoesters deserve investigation as complete insulation systems rather than only as isolated fluids.

Recent research also raises important questions about how paper life should be defined. Lam et al demonstrated that the apparent thermal class and relative life advantage of thermally upgraded Kraft paper in natural ester depend on the selected end-of-life criterion [48]. A life estimate based on retained tensile strength may not yield exactly the same comparative conclusion as one based on degree of polymerization. Iijima et al further examined additive strategies intended to improve paper durability in natural ester [49]. These findings caution against reducing transformer-life assessment to one ageing marker [48,49].

Most importantly, the oil–paper benefit must be evaluated using actual transformer temperatures. Cilliyuz et al demonstrated that an ester that slows cellulose ageing chemically may simultaneously cause a hotter winding because of poorer fluid circulation [12]. Transformer life therefore depends on the resulting balance. Palm monoesters and engineered low-viscosity formulations are attractive precisely because they could retain favorable moisture–cellulose chemistry while narrowing the thermal penalty.

Oxidation Stability Remains the Principal Long-Duration Fluid Challenge

Oxidative stability remains one of the strongest arguments against treating conventional natural esters as universal drop-in replacements for mineral oil. Unsaturated fatty-acid chains are susceptible to radical oxidation, generating peroxides and secondary products that increase acidity and viscosity. Under severe oxygen exposure, polymerization and gelling can compromise flow and consequently heat removal. Rao et al., demonstrated the importance of gelling during open-beaker accelerated ageing, while Miadonye et al., showed relationships among spectroscopic changes, peroxide value, acid value, viscosity and oxidation stability [27,28].

This challenge does not mean natural esters are intrinsically unsuitable. It means transformer preservation and fluid formulation become part of the technology. Free-breathing configurations that continuously expose oil to atmospheric oxygen represent a more demanding environment than sealed systems. The transformer tank, conservator, gas space and sealing reliability should therefore be considered elements of ester-fluid design. Oxidation performance should also be qualified under representative combinations of oxygen, metals, cellulose, moisture and temperature instead of relying exclusively on one accelerated test.

Antioxidants represent the most mature formulation strategy. Obebe et al., reviewed antioxidant approaches for natural ester transformer fluids and emphasized that additive chemistry, concentration and interactions with the fluid matrix determine effectiveness. Synthetic inhibitors such as 2,6-di-tert-butyl-4-methylphenol (BHT) and tert-butylhydroquinone (TBHQ) have been widely examined, but the optimum package depends on the ester and service condition [50]. Oparanti, Fofana and Jafari, for example, combined canola oil, palm-kernel methyl ester and antioxidants to obtain a substantially lower-viscosity formulation with improved thermo-oxidative stability and useful dielectric performance [47]. A 2025 experimental study of butylated hydroxytoluene and citric acid in a commercial natural ester further showed that antioxidant selection can alter AC breakdown statistics as well as oxidation control, underscoring the need to co-optimize electrical and chemical performance [51].

Recent hydrolytic and oxidative studies reinforce the need to distinguish degradation mechanisms. Szczesniak and Przybylek investigated changes in physicochemical and dielectric properties and chemical structure under controlled hydrolytic and oxidative ageing [52]. The transformer designer must therefore consider oxidation, hydrolysis and thermal decomposition as overlapping but distinct pathways. A formulation optimized against oxidation alone may still behave differently under sustained moisture or electrical fault conditions.

Ester-Specific Fault Chemistry Is Required for Reliable Dissolved-Gas Analysis

Dissolved-gas analysis (DGA) is fundamental to transformer condition monitoring because electrical and thermal faults generate characteristic gases. Yet natural-esters' molecular structure differs so substantially from mineral oil that identical faults do not necessarily generate gases in identical ratios. Palm-specific molecular work is particularly useful here. Zheng et al., simulated palm-olein pyrolysis and assessed the influence of moisture [29]. Zheng et al., subsequently modelled major palm-oil molecules—including tripalmitin, trilinolein, triolein and tristearin—to identify thermal decomposition pathways relevant to transformer fault analysis [30].

These studies demonstrate why ester DGA requires mechanistic interpretation. Ester bonds, unsaturated chains and β-hydrogen-containing structures generate reaction pathways absent from conventional paraffinic or naphthenic oils. Thermal decomposition can therefore generate "stray gases" even without a transformer fault severe enough to justify conventional mineral-oil alarm interpretation. Turkmen, Secen and Yalcin examined reaction kinetics and gassing tendency of FR3 under thermal stress and explicitly highlighted the diagnostic difficulties caused by stray gassing [31].

Jiang et al., approached the problem from molecular engineering by investigating suppression of stray gas through ester-component regulation under coupled electro-thermal-fluid fields [53]. This suggests a particularly valuable future direction: transformer-fluid design may target not only viscosity, oxidation and breakdown strength but also diagnostically cleaner decomposition behavior. A fluid that generates less ambiguous background gas could substantially improve online condition monitoring.

Condition-monitoring methods should consequently combine DGA with moisture, acidity, viscosity, dielectric spectroscopy, optical spectroscopy, partial-discharge signatures and temperature history. Amalanathan et al., showed that ultraviolet and fluorescence characteristics of thermally aged natural ester correlate with deterioration, while Miadonye et al., demonstrated relationships between infrared spectral information and oxidation-related quality parameters [28,40]. The transition toward sensor-rich transformers could therefore compensate for some limitations of conventional single-indicator diagnostics.

Nanoparticle Modification Offers Powerful Property Enhancement but Introduces a Second Reliability Problem

Nanofluid research has produced some of the most impressive laboratory improvements reported for ester-based dielectric fluids. Proposed mechanisms include electron trapping, modification of charge mobility, interfacial polarization, altered streamer behavior and improved thermal conductivity. Jacob, Preetha and Krishnan, Adekunle and Oparanti, Farade, Wahab and Mansour and Guo et al., collectively show that nanomodification has become a major research direction for natural ester insulation [1,6,8,16].

Palm-derived fluids have participated directly in this development. Oparanti, Khaleed and Abdelmalik prepared palm-kernel-oil-based nanofluids using Al_2O_3 and TiO_2 and identified concentrations at which dielectric performance improved. Siddique, Basu and Basak demonstrated improvement in the dielectric behavior of vegetable-oil/mineral-oil blends containing TiO_2 or ZnO. Maneerot et al., evaluated polarization and conduction behavior in mineral-oil and natural-ester nanofluids [53-55]. These results support the proposition that nanoparticles can regulate charge processes rather than simply add a thermally conductive solid phase.

Surface modification has become increasingly important because direct dispersion can produce aggregation. Chen et al., used surface-modified hexagonal boron nitride and reported simultaneous improvements in electrical characteristics and thermal conductivity, with molecular simulations suggesting stronger nanoparticle–ester interfacial interactions [56]. Koutras et al., emphasized that ageing influences the permittivity, thermal and lightning-impulse behavior of nanofluids, demonstrating why initial enhancement cannot be assumed to remain constant through service [57].

The newest studies move further toward interface engineering. Marisargunam et al., investigated Al_2O_3-enhanced natural ester through accelerated ageing and Weibull analysis [58]. Lan et al., examined surface-modified graphene oxide and temperature-dependent dielectric/thermal mechanisms [59]. Liu et al., reported that KH550 surface-modified SiO_2 improved several dielectric metrics and thermal-ageing resistance in a binary renewable natural-ester system at an optimized low concentration [60]. These advances indicate that nanoparticle surface chemistry may be as important as particle identity.

Yet nanomodification produces a second qualification problem: stability of the enhancer itself. Transformer fluids must remain reliable for decades, whereas many nanofluid studies observe dispersion for days, weeks or months. Agglomeration, sedimentation, interaction with cellulose pores, filtration, reclamation, electric-field-driven migration, chemical ageing, and maintenance procedures remain incompletely resolved. Reclamation studies such as Samikannu et al., show possible routes for managing degraded natural esters, but a grid operator must know how a nano-enabled fluid behaves through the entire maintenance and refurbishment cycle [61].

Figure. 4 represents transformer-fluid development as a multi-objective optimization problem. A formulation cannot be classified as superior merely because one axis—such as breakdown voltage—extends farther than that of mineral oil.

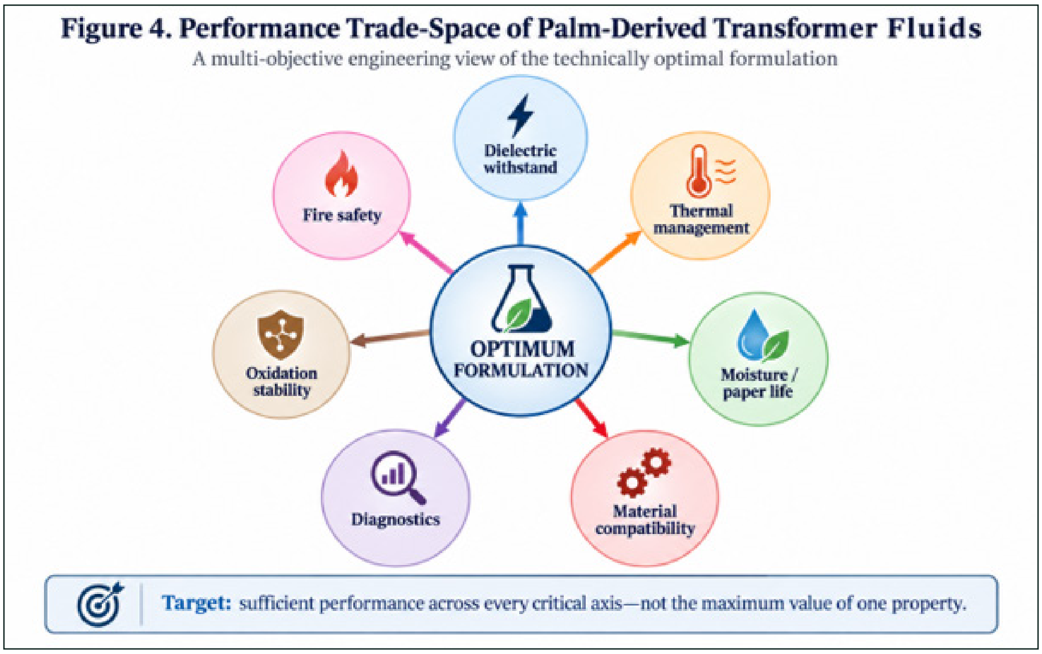

Figure 4: Performance Trade-Space of Palm-Derived Transformer Fluids.

Figure. 4 explains that palm-derived monoesters may improve thermal circulation, antioxidants may improve oxidation stability, and nanoparticles may improve dielectric or thermal behavior. Each intervention can nevertheless modify permittivity, loss factor, ageing products, diagnostic gases or material interactions. The technically optimal fluid is therefore one that achieves sufficient performance on every critical axis rather than maximal performance on one.

Discussion and Analysis

What Does the Evidence Actually Establish?

The literature establishes that palm-derived materials are technically credible candidates for transformer insulation, but it does not establish that any generic palm oil can be deployed interchangeably with mineral oil. The distinction is fundamental. Processed palm oils can reach competitive breakdown strengths; PFAE can provide lower viscosity and promising impulse behavior; PKOME can support transformer heat-transfer applications; and palm-kernel-derived formulations can be combined with antioxidants and nanoparticles. However, each of these is a different material with a different property profile [9,10,33,15].

This leads to the first major answer to the research questions: the engineering unit of analysis should be the standardized palm-derived formulation, not palm oil as an agricultural commodity. A transformer manufacturer requires defined fatty-acid composition, ester structure, moisture specification, antioxidant package, acidity, viscosity, dielectric loss, breakdown probability and manufacturing tolerance. Variability that is acceptable in food or commodity markets may be unacceptable in high-voltage insulation.

The second answer is that dielectric feasibility is more mature than complete transformer-system qualification. Palm studies demonstrate strong AC breakdown results, useful impulse performance and, in modified PFAE, encouraging long-gap behavior. Yet electrical performance also includes partial discharge, streamer velocity, space charge, moisture transients, gas bubbles, ageing and field redistribution. The 2024 PFAE long-gap result is particularly important because it challenges the assumption that ester fluids must necessarily remain confined to lower-voltage applications, but it should be reproduced across electrode geometries, laboratories, production batches and full transformer insulation structures before becoming a design rule [15].

The Cellulose-Life Advantage Must be Evaluated Against the Thermal Penalty

The literature often presents two propositions independently: natural esters may prolong cellulose life, and natural esters are more viscous than mineral oil. In an operating transformer, however, the propositions are mathematically linked through temperature. Cellulose ageing accelerates with temperature, so a chemically protective liquid that causes a hotter winding may lose part of its theoretical ageing advantage.

This explains why the identical-transformer study of Cilliyuz et al., is especially consequential [12]. It does not invalidate the cellulose-ageing benefit; instead, it reframes it as an outcome that must be measured under realistic thermal loading. The same principle appears in thermo-fluid simulations such as Garelli et al., Consequently, Stage 2 qualification of palm-derived fluids should include full temperature-rise tests at rated and overload conditions, hot-spot measurements, cooling-duct velocity or validated CFD, and subsequent conversion of the actual thermal profile into cellulose-life estimates [13].

This coupling gives palm monoesters a strategic advantage. If PFAE or PKOME formulations can approach mineral-oil-like viscosity while retaining ester moisture affinity, high fire point and favorable oil–paper chemistry, they may offer a better total optimization than unmodified high-viscosity triglycerides. However, the price of that viscosity improvement may appear elsewhere, particularly in oxidative stability, flash point, volatility or material compatibility. The engineering objective is therefore not simply “lower viscosity,” but the minimum viscosity compatible with acceptable oxidation, dielectric and fire-safety requirements.

Oxidation Should Be Treated as an Equipment-Design Issue, not Merely a Fluid Defect

Poor oxidation stability is frequently described as an inherent disadvantage of natural esters. Chemically this is justified, especially for unsaturated triglycerides. From an engineering standpoint, however, oxidation depends on oxygen availability, temperature, catalytic metals, antioxidants and preservation system. A sealed ester transformer is therefore not chemically equivalent to an open-breathing laboratory beaker.

This distinction matters for palm-derived esters because feedstock and molecular modification can be combined with transformer design. Antioxidants can delay radical oxidation; lower-unsaturation fractions can improve stability; sealed tanks can reduce oxygen ingress; and online monitoring can detect evolving acidity or viscosity before fluid circulation becomes compromised. Obebe et al., demonstrate how broad the antioxidant design space has become, while Oparanti, Fofana and Jafari demonstrate its application in a formulation containing palm-kernel ester [47,51].

A rigorous qualification program should nevertheless assume imperfect service conditions. Seals age, conservator systems fail, temperature excursions occur and maintenance introduces air. Candidate fluids should therefore be tested not only under ideal sealed conditions but also under controlled oxygen ingress, moisture and copper exposure. Open-beaker gelling studies are harsh, but they identify a credible failure mode that should inform preservation-system requirements [27].

Retrofilling and Purpose-Built Ester Transformers Should be Treated as Different Applications

Retrofilling offers an attractive pathway to reduce fire and environmental risk without replacing the transformer. Yet the existing mineral-oil transformer retains its original winding channels, clearances, impregnated cellulose, cooling design and residual oil. Natural ester changes viscosity and permittivity simultaneously. Montero, García and Burgos demonstrated that electric-field margins can increase in some regions and decrease in others after retrofilling because oil and paper permittivities change differently [45]. Karaman et al., likewise showed that aged mineral oil mixed with new natural ester creates intermediate dielectric and viscosity behavior [46].

Consequently, retrofill qualification should include residual-mineral-oil concentration, mixed-fluid properties, dielectric field modelling, temperature rise, seal compatibility and revised DGA interpretation. By contrast, a purpose-built palm-ester transformer can be designed from the outset around the selected liquid. Larger cooling channels, different radiator sizing, revised insulation clearances and potentially higher thermal-class utilization can convert some apparent fluid disadvantages into manageable design parameters.

This distinction also affects economic assessment. A new transformer does not need the ester to reproduce mineral oil exactly if the transformer itself is optimized for the ester. The relevant benchmark becomes system-level cost, reliability, fire risk, environmental exposure and usable loading—not fluid equivalence.

Emerging Molecular Engineering Changes the Development Pathway

Recent computational studies suggest that future ester development will be increasingly rational rather than empirical. Ye et al., and Ye et al., connect molecular electronic structure to lightning-impulse behavior [15,19]. Jiang et al., connect molecular structure with low-temperature flow [21]. Liu et al., applied generative deep learning and multiscale screening to identify candidate ester structures with substantially lower predicted viscosity [23]. Ye et al., further proposed microscopic parameters for evaluating insulating-oil thermal stability [62].

These developments make palm feedstocks especially interesting because the oleochemical industry already possesses fractionation, esterification, transesterification and blending capabilities. The future transformer fluid may therefore be "palm-derived" without chemically resembling untreated palm oil. A targeted fluid could use selected fatty-acid fractions, engineered ester cores, antioxidant packages and controlled minor components. The role of palm becomes that of a renewable molecular feedstock platform.

This shift also changes how sustainability should be discussed. The engineering review should avoid assuming that renewable feedstock automatically guarantees a superior environmental outcome. Feedstock traceability, land-use governance, refining energy, additive toxicity, fluid lifetime, recyclability and end-of-life management remain relevant. Nevertheless, from the transformer perspective, biodegradability and high fire point can have direct operational value by reducing consequences of leakage or fire in urban, forest, water-sensitive and renewable-energy sites.

Renewable-Energy and Tropical-Grid Applications

Renewable-energy systems provide several high-value application niches. Wind turbines, solar substations, battery-energy-storage interconnections and compact urban substations can place transformers in locations where fire safety, environmental leakage and footprint are particularly important. Natural esters have already attracted attention because their higher fire points can permit alternative installation arrangements and their environmental characteristics are attractive near sensitive ecosystems.

Palm-derived esters may be particularly suitable for tropical grids because low-temperature limitations are less severe than in cold climates. Nevertheless, tropical conditions introduce their own challenges: high ambient temperature increases oxidation rates, humid environments increase moisture-management demands, and rapid renewable-output fluctuations create cyclic thermal loading. The tropical argument should therefore not be that palm ester is naturally "matched" to the tropics, but that cold-flow constraints may be less dominant while oxidation, moisture dynamics and cooling become more important.

At the opposite end of the temperature spectrum, cold-flow limitations remain relevant for export markets and offshore wind environments. Yang et al., investigated pour-point improvement strategies, while Jiang et al., demonstrated how molecular structure can be redesigned for low-temperature mobility [20,21]. A commercially scalable palm-based ester should therefore specify climate class rather than being marketed as one universal formulation.

Toward Ester-Specific Digital Condition Monitoring

Digital monitoring can reduce uncertainty associated with new fluids. Online temperature, moisture, dielectric-loss, partial-discharge and dissolved-gas data can provide a richer view of condition than periodic oil sampling alone. The challenge is to develop ester-specific baselines. A machine-learning diagnostic model trained predominantly on mineral-oil transformers could incorrectly interpret normal ester ageing or stray gassing as a fault.

The next generation of palm-ester field trials should therefore generate openly structured or utility-shared datasets linking loading, winding temperature, moisture saturation, DGA, acidity, viscosity, dielectric spectroscopy and maintenance outcomes. Those datasets would serve two purposes:

validation of the fluid and training of transformer-health models. Palm-oil-producing countries could create a particularly valuable research ecosystem by coordinating oleochemical manufacturers, transformer manufacturers, universities, standards laboratories and utilities.

Palm-Ester Grid Qualification Ladder

The central practical contribution of this review is a proposed eight-level qualification ladder. The objective is to prevent promising bench-scale results from being interpreted prematurely as evidence of grid readiness.

Level 1 — Molecular and compositional qualification
The formulation should have a reproducible chemical identity. Required information should include fatty-acid composition, ester class, molecular-weight distribution, saturation/unsaturation profile, antioxidant package and relevant minor components. Production batches should remain within defined tolerances.

Level 2 — Standard fluid-property qualification
The candidate must satisfy defined requirements for breakdown voltage, dielectric loss, resistivity, permittivity, viscosity, pour point, moisture, acidity, flash/fire point, thermal conductivity, density, oxidation stability and corrosive contaminants. Statistical distributions, not only arithmetic means, should be reported.

Level 3 — Multistress dielectric qualification
The formulation should be tested under AC, DC where relevant, positive and negative lightning impulse, long oil gaps, nonuniform fields, partial discharge, temperature extremes, controlled moisture, particles and bubbles. Accelerated-aged fluid should repeat the critical tests.

Level 4 — Oil–paper and material compatibility
Kraft paper, thermally upgraded paper, pressboard, copper, coating systems, gaskets, elastomers and other construction materials should be aged together with the fluid. Degree of polymerization, tensile strength, acidity, moisture, furans, dielectric response and material dimensions should be monitored. Recent distribution-transformer compatibility testing also supports systematic assessment of candidate fluids against the actual solid, metallic, coating, sealing, and elastomeric materials used in transformer construction [63].

Level 5 — Ageing and diagnostic validation
The candidate should undergo hydrolytic, oxidative, thermal and electrical ageing. DGA fingerprints, stray gassing, spectroscopy, acidity, viscosity and moisture-equilibrium models should be established so that utilities can diagnose the fluid in service.

Level 6 — Full-transformer qualification
Prototype transformers should be subjected to routine and type tests plus instrumented temperature-rise and loading tests. Hot-spot temperature should be measured directly where feasible. CFD models should be validated against physical measurements rather than used as stand-alone evidence.

Level 7 — Controlled field demonstration
A fleet of transformers should be installed across representative environments and duty cycles. Distribution transformers, renewable substations, urban fire-sensitive installations and tropical high-load locations would provide logical early applications.

Level 8 — Fleet-scale qualification
Only long-duration operational evidence across multiple manufacturing batches, transformer designs and locations can establish mature grid reliability. Fluid reclamation, retrofill procedures, sensor interpretation, maintenance intervals and end-of-life handling should be incorporated.

Figure. 5 converts the literature synthesis into a practical technology-development pathway. It also makes explicit that evidence maturity must increase stepwise from molecular specification and laboratory validation to field deployment and fleet-scale reliability.

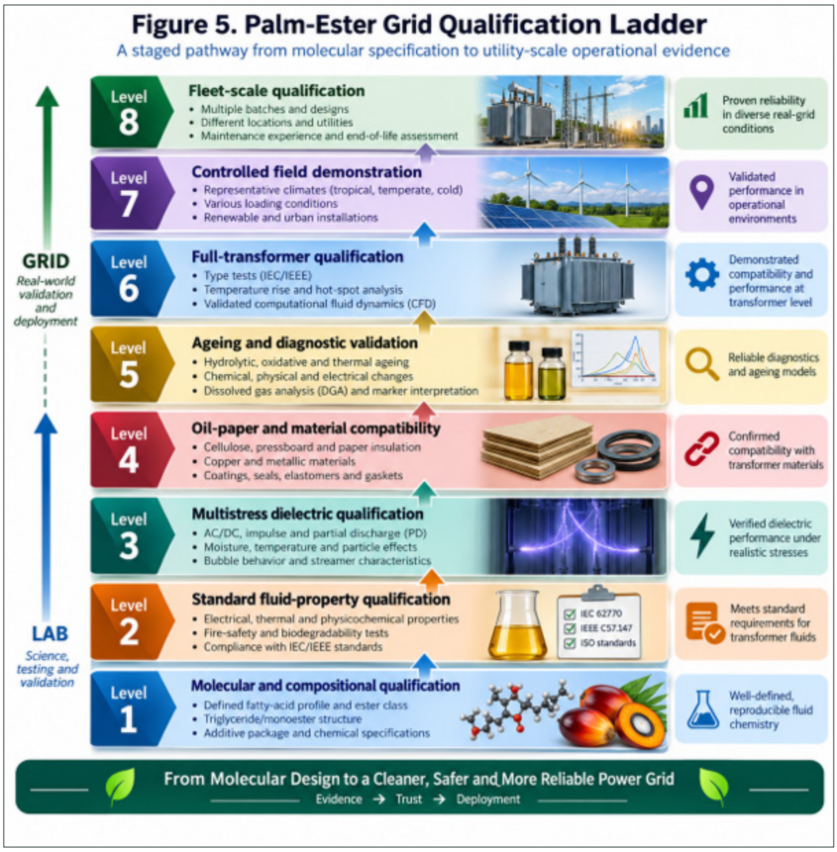

Figure 5: Palm-Ester Grid Qualification Ladder.

Figure. 5 explains that much of the current palm-specific evidence remains concentrated between Levels 1 and 4, with selected studies progressing toward transformer-scale thermal validation. The critical gap lies between technically successful fluid or oil–paper experiments and long-duration fleet evidence. Progress should therefore be measured by movement up the qualification ladder rather than by publication of increasingly high laboratory breakdown voltages.

Research Agenda for Next-Generation Palm-Ester Transformers

Future research should first establish standardized palm-derived reference fluids. Comparison across studies is currently weakened because one publication may test crude palm oil, another RBD palm olein, another modified PFAE and another PKOME. A small number of well-defined benchmark formulations would allow laboratories to reproduce breakdown, ageing, oxidation and thermal tests and identify true methodological differences.Second, long-duration multifactor ageing is needed. Transformer fluids are simultaneously exposed to paper, copper, moisture, oxygen, electrical fields and temperature. Experiments that isolate one factor provide mechanistic knowledge but may miss interactions. A coordinated test matrix should vary moisture and oxygen while including cellulose and copper, with periodic AC/impulse/PD measurements and chemical analysis.

Third, palm-derived fluids require transformer-scale thermal validation. The evidence from natural esters shows clearly that viscosity can undermine heat transfer. PKOME and PFAE provide promising lower-viscosity routes, but they should be tested in instrumented transformers across realistic loading profiles. Thermal design optimization should proceed in parallel rather than after a final fluid formulation is selected.

Fourth, ester-specific diagnostic standards should be developed. Palm-oil and natural-ester pyrolysis research shows that gas-generation mechanisms differ from mineral oil. Future field demonstrations should continuously link DGA with verified operating states and fault events. This will allow development of ester-specific alarm thresholds, fault ratios and probabilistic diagnostic models.

Fifth, nanoenhancement research should shift from short-term maximum-property experiments toward reliability-centred nanofluid engineering. Stable surface functionalization, nanoparticle–cellulose interaction, sedimentation under thermal cycles, electric-field migration, filtration and reclamation require attention. The 2025–2026 literature indicates that surface-modified nanoparticles can significantly improve interfacial control, but multi-year stability remains the decisive test [8,59,60].Sixth, computational design should be integrated with palm oleochemistry. Generative models and molecular dynamics can screen candidate ester structures before synthesis, but their predictions need experimental calibration. Palm fatty-acid fractions offer a practical molecular library for this purpose. Candidate structures should be optimized simultaneously for viscosity, oxidation stability, flash point, electronic properties, moisture behavior and biodegradability rather than for one property alone.

Finally, pilot deployment should prioritize applications in which the distinctive advantages of natural esters have the highest system value. Distribution transformers in environmentally sensitive locations, urban indoor substations, renewable-energy installations, tropical networks and fire-sensitive infrastructure are logical first targets. High-voltage power-transformer deployment can follow once long-gap impulse, thermal design, DGA and long-duration ageing evidence become sufficiently mature.

Conclusion

Palm-oil-derived natural esters have progressed beyond the stage at which their feasibility as transformer liquids should be judged solely by asking whether vegetable oil can withstand electrical stress. Contemporary evidence demonstrates that palm-derived triglycerides, palm olein, palm fatty-acid esters and palm-kernel-oil methyl esters can provide technically valuable combinations of dielectric performance, fire safety, renewability, biodegradability and moisture interaction. Chemical conversion and formulation can also address important limitations of untreated vegetable oils.

The central challenge is now engineering integration. High breakdown voltage is insufficient if viscosity produces excessive hot-spot temperatures. High moisture solubility is advantageous only when dynamic saturation and partial-discharge risks are understood. Longer cellulose life must be assessed at actual transformer temperatures rather than equal-temperature laboratory conditions. Oxidation stability must be integrated with antioxidant chemistry and preservation-system design. DGA requires ester-specific interpretation, while nanoparticle enhancement requires evidence of long-term dispersion and maintenance compatibility.

Palm-derived monoesters and chemically modified PFAE appear particularly promising because molecular engineering can reduce viscosity and alter impulse behavior without abandoning the renewable palm feedstock platform. However, the fluid should be designed together with the transformer rather than treated as a simple mineral-oil replacement.The proposed Palm-Ester SPPQ Framework and Grid Qualification Ladder therefore reposition the research question from “Can palm oil work as transformer oil?” to “Which standardized palm-derived molecular formulation, transformer design, diagnostic regime and qualification pathway can deliver dependable service at a defined voltage, loading and environmental class?” Answering that question requires coordinated work among oleochemical producers, high-voltage laboratories, transformer manufacturers, utilities, universities and standards organizations. If that qualification pathway is completed, palm-derived esters could evolve from an alternative bio-based liquid into a high-value engineering material for safer and more environmentally compatible power systems.

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