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Technical and Operational Challenges in the Deployment of Natural Ester Insulating Fluids in Power Transformers

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Abstract

Natural ester insulating fluids derived from vegetable oils have gained significant attention due to their biodegradability, high fire safety, and capability to enhance the shelf-life of solid insulation. However, transforming these fluids into a trustworthy replacement for mineral oil requires resolving several technical challenges. Key issues include oxidation instability due to the presence of unsaturated fatty acid composition, moisture absorption due to their hygroscopic nature, and limitations for usage at high altitudes. Additional barriers include thermal ageing uncertainties, impurities and pigment content, variability in feedstock, compatibility with transformer construction material, and the lack of optimised transformer-grade additive packages. Gaps in cost considerations and limited long-term field-performance data further affect adoption. Addressing these issues via state-of-the-art stabilisation technologies, improved processing techniques, additive engineering, control strategies for moisture, and NE-specific design and testing methodologies is essential for enabling reliable and sustainable deployment of natural ester fluids in the power sector.

Keywords: Additives, Natural Ester Fluids, Standardisation, Sustainable Transformer Fluids, Transformer Insulation, Vegetable Insulating Oils

1. Introduction

Mineral oil has been extensively used as an insulating and cooling medium in power transformers due to its improved physico-chemical properties. The widespread availability of mineral oil and its comparatively lower cost contribute to its continued dominance in transformer applications. Natural Ester (NE) insulating fluids derived from vegetable oils have emerged as a promising class of dielectric liquids for power transformers, driven by environmental regulations, fire-safety requirements, and the global shift towards viable materials[1-3]. Figure 1 illustrates a comparative overview of the key characteristics of conventional mineral oil and vegetable-based insulating fluids used in transformer applications. Their inherent biodegradability and high fire point provide safety advantages, while their chemical structure allows improved thermal protection of paper insulation[4,5]. The ability of NE fluids to retain higher moisture without proportionally degrading cellulose is particularly beneficial in enhancing the shelf-life of the transformer[5].

However, several technical constraints continue to limit extensive adoption. Natural esters are chemically more susceptible to oxidation due to their high degree of unsaturation[3,6], and their hygroscopic nature significantly increases moisture absorption compared to mineral oils[2,4].

Their relatively high viscosity and poor low-temperature performance restrict usage in cold climates and high-voltage applications[3]. Feedstock variability related to crop origin introduces inconsistencies in fluid properties[7]. Natural pigments, trace metals, and residual impurities further affect stability and dielectric strength.

Material compatibility with transformer construction materials, viz., press board, Kraft paper, *etc*., also requires deeper investigation. Although NE fluids exhibit favourable interaction with cellulose[4,5], their interactions with elastomers, metals, and coatings can differ between manufacturers[8]. Limited long-term field data and incomplete

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understanding of degradation pathways remain barriers for large-scale deployment of NE's[6,9].

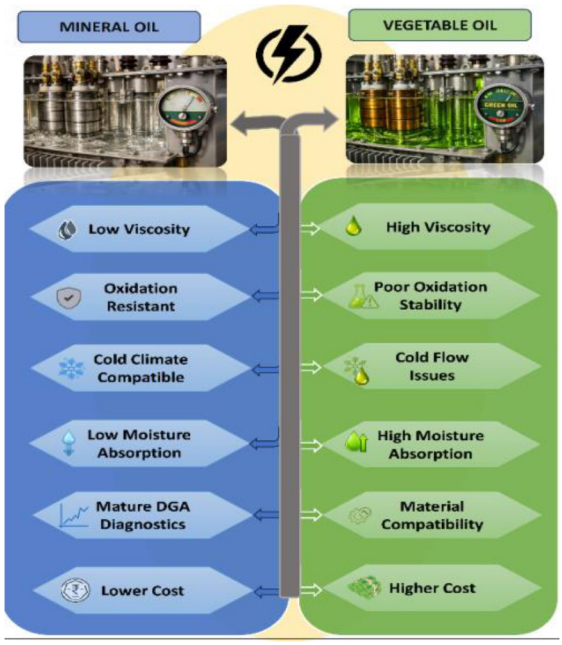


Figure 1. Vegetable vs mineral oil as a dielectric fluid.

Therefore, addressing these confines through improved stabilisation, processing techniques, additive design, moisture control, and transformer-specific engineering is essential. This paper consolidates the technical challenges of NE fluids and identifies pathways to support their ecological adoption in future transformer and other power equipment.

Growing environmental concerns and fire-safety requirements have increased interest in biodegradable insulating fluids. Mineral oil, although widely used, is non-biodegradable and highly flammable, presenting environmental and operational risks. Natural esters offer >95% biodegradability and significantly higher fire points, making them inherently safer[1-3]. They also slow cellulose ageing, an effect well documented in long-term studies[4,5].

Despite successful deployment in distribution transformers, their use in high-voltage and cold-region applications remains conservative. Utilities and manufacturers require stronger evidence and standardisation before adopting NE fluids for critical grid infrastructure, reinforcing the need for comprehensive research.

2. Technical Challenges in Transformer Applications

While many properties are promising, some features have challenges, as shown in Figure 2 and require improvement as discussed:

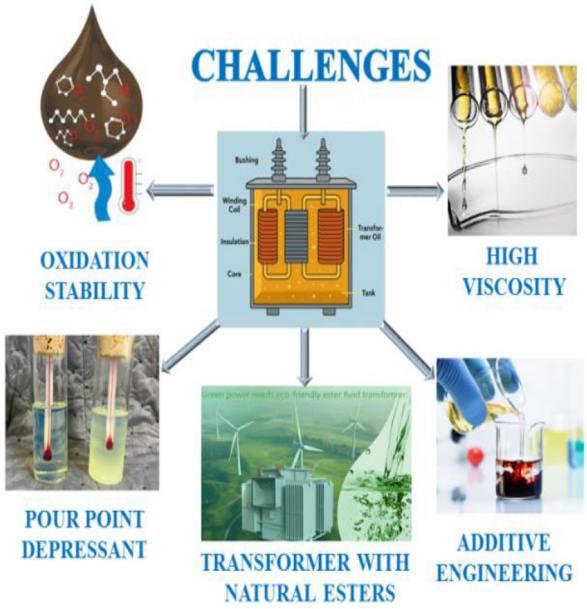


Figure 2. Technical challenges of vegetable oil for transformer application.

2.1 Oxidation Stability

NE fluids oxidise readily due to unsaturated fatty acids[3,6]. Oxidation leads to an increase in acidity, leading to sludge formation[10], and viscosity rises, especially in transformers exposed to oxygen ingress. Antioxidant packages tailored for mineral oils are not fully effective for NE chemistry[6]. Use of antioxidants, regular monitoring, and possibly developing stabilised vegetable fluid formulations will improve the stability of vegetable fluids towards oxidation.

2.2 Moisture Sensitivity/Water Absorption

Vegetable oils tend to absorb/retain more moisture, which degrades dielectric properties. Some studies show that vegetable oil's moisture content must be significantly reduced to meet standards. Good processing, dehydration, storage, sealing, and moisture

monitoring. Studies reveal that NE fluids can absorb up to 10 times more moisture than mineral oils. Although this benefits cellulose insulation[5], it increases risks such as:

- Reduced dielectric strength
- Bubble formation under thermal stress
- Accelerated hydrolysis of esters
- Moisture-equilibrium models developed for mineral oil are not directly applicable[11].

2.3 Acidity/Stability over Time with Ageing and Oxidation

Acidity increases, which can compromise insulation properties. In some of the recent reports, vegetable oils have higher initial acidity compared to mineral oils. However, in one of the recent studies by Gnanasekaran *et al.*,[12] *Pongamia Pinnata* Oil (PPO) processed by the percolation method, a physical method, has improved the acidity and ageing characteristics and found that measured parameters meet the requirements of IEC 62770. Further, improvements are required to control acidity in the long run; periodic replacement or reconditioning.

2.4 Low-Temperature Performance

Vegetable oils may have poorer pour points (more likely to gel or high viscosity at low temperature) (−10°C to −21°C) compared to mineral oils (−45°C). For PPO, studies report that the pour point is not as low. May limit cold climate use; however, can improve these properties by doping additives (Pour Point depressants), pre-heating or blending for cold performance. Literature highlights flow and pumping challenges during cold starts[3]. This limits use in extreme climates without doping additional additives or redesign.

At lower temperatures (*e.g.* around 40°C), Vegetable oils have a significantly higher viscosity than mineral oil[12]. This can lead to slow circulation, reduced cooling performance, increase losses. Needs better purification, perhaps modifications or blending; the design of transformer cooling must account for this.

2.5 Feedstock Variability

Vegetable-oil-based fluids vary with region, cultivation, and processing conditions[7]. Fatty acid profiles affect oxidation stability and viscosity, requiring tight refining controls.

2.6 Impurities and Pigments

Natural pigments, trace metals, and sterols catalyse degradation reactions and complicate purification. To eliminate impurities and pigments, advanced bleaching and degumming techniques are essential.

2.7 Material Compatibility

NE fluids demonstrate strong compatibility with cellulose but exhibit variable interaction with other transformer materials. However, certain elastomers, paints, and metals show inconsistent compatibility with NE fluids[8], requiring further study and standardisation. Interactions between NE fluids and elastomers vary widely[9]. Copper, Aluminium, and surface coatings may exhibit differing ageing patterns in natural environments.

2.8 Research Gaps

Research gaps need to be addressed in the following areas:

- Oxidative stability at high temperatures
- Additive requirements
- NE-specific ageing models
- Dissolved gas interpretation differences
- More comprehensive test methods are needed for high-voltage applications[1,2].

3. Pathways for Improvement

3.1 Chemical Stability

Currently anti-oxidant such as DBPC, DBDS, etc. are used in both natural esters and mineral oils. However, there are no specific antioxidant additives for doping in natural esters. Hence, advanced antioxidant systems, including natural phenolics and metal deactivators, can significantly improve oxidation/chemical stability[6]. Hence, further studies on chemical stability are required for effective usage of Natural esters as an alternative to mineral oil in transformer applications.

3.2 Processing Techniques

Short-path distillation, bleaching, and enzyme-assisted refining processes help in removing pigments and trace impurities[7]. Recently, Gnanasekaran *et al.*[12] initiated a facile percolation technique for the removal of colour and unwanted impurities with improved properties.

3.3 Additive Engineering

Performance of NE's is highly dependent on additive engineering[14-17], which modifies various properties. Tailored antioxidant additives include both synthetic (TBHQ, BHT and BHA) and natural (Tocopherols, rosemary extract, ascorbic palmitate), moisture control additives (Molecular sieves in formulations, Polyglycol-based water absorbents, reactive desiccant additives -oxazolines, epoxides)[18,19]. Pour point depressants (PPD's-Alkyl methyl acrylate polymer, Poly ester-based flow improvers, Co-polymer of Ethyl-vinyl acetate), Metal deactivators (Benzotriazole derivatives, Tolyltrizole, Salicylaldoxime). Presence of FFA and Phospholipids in Vegetable oils leads to the formation of foam if the oil undergoes immature processing, which further leads to restricting the processing technique, involving the compromise of the quality of the product and possibilities to overflow the oil during the operation of the transformer, leading to damage of the transformer. Polyglycol and silicones antifoams are the best possible anti-foaming agents to resolve the issues effectively and efficiently associated with foaming challenges, either during processing or usage of the transformer, in terms of the following parameters:

- Oxidation control
- Moisture management
- Cold-flow improvement
- Metal deactivators
- Foam suppression

A synergetic blend of phenolic and natural antioxidants often provides the best balance for long-term transformer operation[20-22]. PPD's interfere with crystallisation of saturated fatty acid chains, thus improving low-temperature pour point and cold cranking characteristics[23,24]. Metal activators form a passivation film on metal surfaces, causing surprising catalytic degradation and sludge formation[25,26]. However, additive engineering experiences various challenges regarding miscibility, interaction between additives and solid insulation, compliance with national/

Table 1. General comparison of various vegetable oils used as transformer oils

Vegetable Oils	Dielectric Strength	Oxidation Stability	Thermal Stability	Viscosity	Biode gradability	Refer ences
Soybean oil	Moderate (Good for medium voltage applications)	Moderate	Moderate	High	Biodegradable	3,6,19
Canola oil	High (Better for high-voltage transformers)	High (Improved with antioxidants)	Moderate (Can degrade under high stress)	Moderate	Biodegradable	17, 30
Pongamia Pinnata oil	High (Excellent dielectric strength)	Very High (Low tendency to oxidise)	Moderate (Sensitive to low temperatures)	High	Biodegradable	12, 31-33
Jatropha oil	High (Suitable for high-voltage transformers)	High (Requires additives for stability)	High (Good thermal performance)	High	Biodegradable	34,35
Rapeseed oil	High (Good for high-voltage applications)	High (Good for long-term use)	High (Stable under varying conditions)	Moderate	Biodegradable	36
Sunflower oil	Moderate (Suitable for lower-voltage transformers)	Low (Prone to oxidation)	Low (Requires antioxidants)	High	Biodegradable	13
Olive oil	High (Excellent dielectric strength)	Very High (Oxidative stability)	High (Resistant to temperature degradation)	High	Biodegradable	3
FR3	High - comparable or better than mineral oil	High	High	viscosity closer to mineral oil and better thermal behaviour	Highly biodegradable	37

international standards, and compromise of biodegradability of NE's. However, research is in an early stage on bio-derived antioxidant additives, nano-engineered stabilisers to improve oxidation, and antioxidant regeneration systems embedded in ester matrices[27,28].

3.4 Adaptation of Transformer Design

Future transformers may incorporate:

- Nitrogen blanketing
- Improved cooling-duct geometries
- Thermal Design Adaptation (Critical Step)
- Dielectric Design Adaptation
- Insulation coordination
- Moisture management
- Paper insulation

3.5 Diagnostic Method Development

NE fluids exhibit different dissolved gas patterns compared to mineral oils. In one of the recent studies, Chenmeng Xiang *et al.*[29] reported that the diagnostic methods developed for mineral oil were not fully understood in evolving the electrical and thermal faults in NE dielectric fluids and emphasised the need for modification of the diagnostic tools. NE-specific DGA interpretation models, moisture-equilibrium curves, and ageing correlations are required.

3.6 Biodegradation Studies

Biodegradation of insulating oils is an important eco-friendly property, indicating the degradation capability. Studies on the biodegradation properties of non-edible vegetable oil insulating-based fluids processed through chemical methods have not been reported earlier.

4. Comparison of Various Vegetable Oils Used in Transformer Applications

General comparison of various vegetable oils as dielectric fluids is described in Table 1 and summarised as follows:

- **Soybean oil** is commonly used due to its good dielectric properties and biodegradability, though it may have issues with oxidation stability over time. **Canola oil** offers a good balance between oxidation stability and dielectric strength but requires antioxidants to perform well at high voltages.
- **Pongamia Pinnata oil** shows excellent dielectric strength and oxidation stability, making it an ideal choice for high-performance transformers.
- **Jatropha oil** has high dielectric strength and thermal stability but may require additives to further improve oxidation resistance.

Table 2. Advantages and disadvantages of various vegetable oils

Vegetable Oil	Advantages	Disadvantages	References
Soybean Oil	- Good dielectric properties - High flash point - Biodegradable - Excellent oxidation resistance at normal operating temperature	- Higher viscosity compared to mineral oils - Prone to oxidation under high temperatures	3, 6
Canola Oil	- High biodegradability - Low pour point - Excellent oxidation stability	- High viscosity compared to mineral oils - Lower thermal stability	38
Jatropha Oil	- Biodegradable - Good dielectric properties - High flash point	- High viscosity - Sensitive to oxidation in the absence of antioxidant additives	34,35,39,40
Rapeseed Oil	- High oxidative stability at normal operating temperature - Excellent dielectric strength - Biodegradable	- Prone to degradation at high temperatures - High viscosity at lower temperatures	27
Sunflower Oil	- Good dielectric properties - Biodegradable	- Poor thermal stability at high temperatures - High viscosity - High cost	13
Pongamia Oil	- Good dielectric strength - High oxidation stability - High flash and fire points -Lower environmental impact - Biodegradable	- High viscosity - Limited use in high-performance transformers	12,41,42,43
Olive Oil	- Excellent oxidative stability - High flash point - Biodegradable	- High viscosity - Expensive and less widely available	3

- **Rapeseed oil** is highly stable under various conditions and is suitable for both low and high-voltage applications.
- **Sunflower oil**, though biodegradable, struggles with oxidation resistance and may require antioxidants for extended use in transformers.

Olive oil provides exceptional dielectric and thermal stability but is less commonly used due to its high cost

5. Advantages and disadvantages of various vegetable oils

Advantages and disadvantages of various vegetable oils as dielectric fluids are described in Table 2.

6. What needs future Research?

Research gaps for using vegetable oils as an insulating/cooling fluid in transformers; with each gap matters, and practical experiments or metrics can be run to address them.

The following are the highlights of the highest-priority items:

6.1 Research needs and must address before mass usage

6.1.1 Long-Term Oxidation/Ageing Behaviour (Bulk Oil + Paper System)

Natural esters oxidise/hydrolyse faster than mineral oils; oxidation products affect acidity, conductivity, and paper ageing. Short-duration lab tests exist, but long-term transformer-level ageing data are sparse for vegetable oil. Need more research focus on accelerated thermal and oxidative ageing on oil + Kraft paper stacks; acidity, interfacial tension, viscosity, oxidation products (GC-MS), and Degree of Polymerisation (DP) of solid insulation.

6.1.2 Paper-Oil Interaction and Cellulose Ageing under Realistic Moisture/Temperature Cycling

Vegetable esters absorb and redistribute water differently than mineral oil (often better for paper life but complex)[44]. NE fluids' impact on paper DP, water profiles within paper, and kinetics under realistic transformer thermal cycles need clarity. More focus on moisture sorption/desorption experiments, paper impregnation studies, dielectric response of paper + oil samples, and measurement of DP and tensile strength after simulated service cycles.

6.1.3 Oxidation Stabilisation Strategy (Antioxidants, Inhibitor Selection and Compatibility)

NE's fatty acid profile determines susceptibility; antioxidants can help, but need compatibility, thermal limits, and no harmful by-products. Recent reviews show that additive work is active, but data is limited[36,38]. Requires screen phenolic and aminic antioxidants and combinations (bench reactor experiments at 90-120°C under O_2), monitor induction time (PDSC), acidity and dielectric properties post-treatment[45].

6.1.4 Dielectric Performance under High Stress - AC/DC/Impulse and Partial Discharge (PD) Behaviour

Small-scale BDV tests exist, but full-fledged characterisation of PD inception, streamer behaviour, and impulse withstand in NE-filled windings (including variation in temperature/moisture) is limited. These determine safe voltage ratings and retrofit feasibility. Needs PD inception/extinction testing on model winding geometries, lightning impulse and switching impulse tests at various temperatures and moisture loadings; compare with mineral oil baseline.

6.1.5 Long-term Ageing Studies

Real time transformer operating conditions (thermal + electrical + moisture + oxygen) need to evaluate vegetable oil degradation performance. To address these issues, our research group is working on a pilot project to study the real-time performance under actual load conditions to explore the suitability of vegetable fluids for transformer applications.

6.2 Necessary for Deployment

6.2.1 Low-Temperature Fluidity and Cold-Start Performance

Viscosity affects cooling and flow in HV transformers; Vegetable fluids can be more viscous at low temps than mineral oil. Need data for regional climates and for the design of pumps/radiators. Need to address the shortcomings raised due to viscosity, pour point, and heat transfer; and there is a need to evaluate pour-point depressants or partial trans esterification to lower viscosity.

6.2.2 *Thermal Conductivity and Cooling Performance in Real Thermal Circles*

Cooling performance (radiator sizing, oil convection) must be validated for load cycles and for hotspots inside windings. Lab-scale thermal conductivity studies do not always predict system behaviour. Long term studies are required on full transformer thermal models validated by thermal run tests on NE-filled prototype transformers (temperature rise, hotspot mapping).

6.2.3 *Gas Generation, DGA Monogram and Fault Diagnostic*

Natural esters change dissolved gas generation and gas composition during faults and ageing — this affects the interpretation of Dissolved Gas Analysis (DGA) and diagnostic thresholds. Needs to develop controlled overheating/fault simulation to record gas species and rates; develop NE-specific DGA interpretation mechanism.

6.2.4 *Material Compatibility*

Natural Esters can swell or interact differently with seals, paints, and paper varnishes used in existing transformers. Compatibility must be evaluated to avoid leakage or mechanical failures. Standardised compatibility tests (ASTM/IEC protocols) across common transformer materials and adhesives at elevated temperatures are to be developed.

6.2.5 *Refill/Retrofit Procedures, Reclamation and Preservative Chemistry*

Retro-filling of existing transformers in the field level requires protocols for flushing, drying, and mixing; it also needs methods to reclaim vegetable fluids after service and to treat degraded oil[46]. Develop and validate flushing solvents/procedures, define mixing limits with mineral oil, and design regeneration processes (adsorbents, filters, ester re-esterification).

7. Recommended Research Directions

7.1 Standardisation and Life Cycle/Techno-Economic Analyses

Utilities need standards for Life Cycle Assessment (LCA) and cost benefit across manufacturing, transport, fire safety, and end-of-life impacts. Use cases differ for distribution and power transformers. Requires studies on LCA comparing mineral oil with other natural esters; draft recommended test matrices for regulators.

7.2 Biodegradation/Environmental Fate of Aged Vegetable Oils and Oxidation By-Products

Vegetable oils are biodegradable; however, aged oil/by-products formed due to oxidation may have different toxicity and fate related to spillage response and disposal needs to be addressed. Biodegradability tests (OECD 301/302) on fresh and artificially aged vegetable oils; eco-toxicity screening of aged fractions to be performed.

7.3 Additive/Nano-modifier Strategies - Improve BDV, Thermal/Rheological Properties

Nano and additive approaches show possibilities to enhance dielectric strength and thermal properties, but long-term effects, sedimentation, and stability are open questions[47,48] and need to be addressed. Bench tests for stability (zeta potential, sedimentation) to be developed, dielectric testing, thermal cycling, and compatibility with paper and evaluate the results for possible implementation in large scale. Need to work out the processing cost, antioxidant additives, and possible blending with other existing dielectric fluids to meet the high-altitude climatic requirements.

7.4 Supply Chain, Consistency of Oil Quality

Since fatty acid composition can vary depending on variety, soil, climate, and extraction process. Vegetable insulating fluids are produced from a wide variety of agricultural feedstock (*e.g.*, soybean, rapeseed, sunflower). Major suppliers operate vertically integrated supply chains, controlling raw material sourcing, refining, chemical modification (*e.g.*, esterification), and final fluid formulation.

Global production capacity supports long-term availability for transformer manufacturing, filling, and maintenance. Multiple qualified suppliers reduce dependency on a single source and help ensure business continuity.

7.5 Safety Regarding Biodegradability

Safety with regard to biodegradability and behaviour in case of spill/ leakage. Need to address deleterious effects

in case of spills or leakages. If not promptly removed, vegetable oils float on the surface of water and the likelihood of the formation of films that may reduce oxygen transfer and harm aquatic life. If left untreated, spills may become rancid, causing odour issues. Prevent spills from entering drains, waterways, or sewers. Encompass spills using absorbent materials such as sand, earth, or commercial oil absorbents. Collect and dispose of waste oil and contaminated materials in accordance with local environmental regulations. Proper handling and spill management are essential to minimise localised environmental effects.

8. Proposed Testing and Field Validation Methodology

- Bench-scale physicochemical and dielectric baseline (BDV, viscosity vs Temp, pour point, oxidation stability, acidity).
- Paper-oil accelerated ageing + DP tests (with and without antioxidants).
- PD and impulse tests on model windings; thermal run tests in prototype transformer.
- Fault/gas generation study and DGA mapping.
- Field pilot retrofit in a low-risk distribution transformer with full monitoring (temps, DGA, oil sampling) at least for 1-3 years.

Parallel LCA, standards mapping, and development of retrofit/reclamation protocols.

9. Conclusions

Natural ester insulating fluids offer substantial potential for enabling environmentally responsible and fire-safe transformer design. However, achieving widespread adoption requires addressing several interconnected challenges, as discussed above: oil chemistry, materials, processing, and standardisation. Oxidation instability, moisture sensitivity, and low-temperature limitations remain the most significant technical constraints. Additional concerns regarding feedstock quality, impurities, pigment content, and long-term compatibility with transformer materials obscure their deployment in high-voltage equipment.

The absence of optimised antioxidant and stabiliser systems tailored for natural esters, as well as insufficient international testing methodologies, continues to limit their reliability assessment. Moreover lack of long-term field performance data restricts utilities and manufacturers from fully evaluating lifecycle benefits and operational risks.

To advance transformer-grade natural ester fluids, future research must focus on improved purification and refining processes, moisture-control strategies, stabilisation chemistry, and development of NE-specific diagnostic tools and aging models. Standardisation bodies must expand and harmonise test methods to address high-temperature operation, cold-start behaviour, and compatibility profiles. Collaborative initiatives across industry partners, research institutions and utilities will be crucial in creating the evidence base required to transition natural ester fluids from niche use to mainstream transformer applications.

By overcoming these challenges, natural ester fluids can serve as a robust and sustainable alternative to mineral oils, contributing significantly to safer, cleaner, and more resilient power systems.

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Author Contribution:

Dr. C. Venkata Prasad: Conceptualization of the study; formulation of the research objectives, literature survey, preparation of original draft. Dr. D. Gnanasekaran: Literature survey support, Critical review of technical content, editing and refinement of the manuscript.All authors have read and agreed to the published version of the manuscript.