



Exploring the Dielectric Strength Enhancement of Virgin Coconut Oil as an Alternative Transformer Liquid Insulation through Nanomaterial Additives

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ABSTRACT

Virgin coconut oil (VCO) is a biodegradable natural ester whose dielectric strength and thermal performance remain below those of mineral oil. This study enhanced VCO with surface-modified TiO₂, Al₂O₃ and SiO₂ nanoparticles (0.01–0.05% w/v), prepared by magnetic stirring and ultra-sonication and characterized by XRD, SEM/TEM, EDX, FTIR, UV–Vis and zeta potential analysis. AC breakdown voltage peaked at 0.03% w/v for all three Nano fluids, reaching 58 kV for TiO₂ (mineral oil: 45 kV; ester oil: 55 kV), an increase of 25–30% over pure VCO. TiO₂ also raised thermal conductivity from 0.32 to 0.38 W/m·K and retained 95% of its initial UV–Vis absorbance after 90 days. No degradation of copper, transformer steel or Kraft paper was observed. TiO₂-VCO Nano fluid is a technically viable, sustainable liquid insulation candidate for distribution transformers.

1. INTRODUCTION

Reliable transformer insulation is essential for the safe and efficient operation of electrical power systems. Transformer insulating liquids provide electrical insulation, dissipate heat generated during operation, and protect internal insulation systems from degradation. For decades, mineral oil has remained the most widely used insulating liquid because of its excellent dielectric properties, favorable cooling characteristics, and relatively low cost. Despite these advantages, mineral oil presents several environmental and operational challenges, including poor biodegradability, high flammability, and dependence on non-renewable petroleum resources [1], [2].

Growing environmental awareness and stricter sustainability requirements have stimulated interest in

biodegradable insulating liquids derived from renewable resources. Natural ester oils have attracted considerable attention because of their excellent environmental performance, high flash points, and reduced fire hazards [2], [3]. Chemically modified palm oil has likewise been examined as a natural ester insulating liquid [4]. Among these alternatives, virgin coconut oil (VCO) offers significant potential due to its wide availability, biodegradability, favorable dielectric behavior, and relatively high oxidation stability [5–7].

Although previous studies have demonstrated the suitability of VCO as an insulating liquid, its dielectric breakdown strength and thermal characteristics remain inferior to those of conventional mineral oil. These limitations reduce its practical application in medium- and high-voltage transformers [3], [6], [7].

Recent advances in nanotechnology have introduced Nano fluids as a promising approach for improving transformer insulating liquids. The incorporation of dielectric nanoparticles into insulating oils has been shown to enhance electrical breakdown strength through electron trapping, suppression of streamer propagation, and improved heat transfer characteristics [8–11]. Nanoparticles including titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), and silicon dioxide (SiO_2) have demonstrated considerable potential for improving transformer insulation performance [3], [10].

This study investigates the enhancement of VCO through the incorporation of dielectric nanoparticles. The research focuses on nanoparticle preparation and characterization, evaluation of dielectric and thermal properties, assessment of compatibility with transformer materials, and comparison with conventional insulating oils, using absolute measured values rather than relative changes alone. The findings contribute to the development of environmentally friendly transformer insulating liquids capable of improving transformer reliability while reducing environmental impact [1], [2], [8].

2. MATERIALS AND METHODS

2.1 Research design

This study employed an experimental, laboratory-based research design to examine the enhancement of the dielectric performance of VCO through the incorporation of dielectric nanoparticles. The methodology comprised four principal stages: preparation of the insulating liquid, formulation of VCO-based Nano fluids, characterization of the nanoparticles and Nano fluids, and evaluation of their dielectric, thermal, and material compatibility properties.

2.2 Materials

VCO (Local supplier) was selected as the base insulating liquid due to its biodegradability, renewable origin, high flash point, and favorable insulating properties. Commercial mineral transformer oil and a commercial ester-based insulating oil were used as reference liquids for comparative analysis. Three

electrically insulating metal oxide nanoparticles were selected as dielectric additives: titanium dioxide (TiO_2), aluminum oxide (Al_2O_3) and silicon dioxide (SiO_2). The nanoparticles had particle sizes ranging from 20 to 50 nm and a purity of at least 99% (Sigma-Aldrich).

2.3 Pre-treatment of virgin coconut oil

Prior to Nano fluid preparation, the VCO was conditioned to improve its dielectric quality. The oil was subjected to vacuum dehydration at temperatures between 80 and 90°C to reduce moisture content. It was subsequently filtered to remove suspended particles and impurities. Moisture analysis was then conducted, and the treated oil had a water content of 12 mg/kg, determined using Karl Fischer titration (ASTM D6304), which met the minimum requirement for transformer insulation testing.

2.4 Preparation of VCO-based Nano fluids

Surface modification of the nanoparticles was performed to improve compatibility with the non-polar VCO and minimize particle agglomeration. The coupling agent was 3-aminopropyltriethoxysilane (APTES, Sigma-Aldrich, $\geq 99\%$ purity, added at 1:10 in ethanol. The reaction was carried out at 70°C for 2hrs under 500 rpm in an ambient atmosphere, after which the particles were washed by centrifugation with ethanol and dried at 80°C for 12hrs. The effectiveness of the surface treatment was verified using Fourier transform infrared spectroscopy (FTIR) and contact angle measurements.

Nano fluids were prepared using a two-step dispersion method. Predetermined quantities of nanoparticles were dispersed into the treated VCO at concentrations of 0.01%, 0.03%, and 0.05% (w/v). The mixtures were first subjected to magnetic stirring for 30minutes at 500 rpm and subsequently ultrasonicated for 60minutes using a probe sonicator 200w, 20kHz with the sample temperature held at 30°C, to achieve uniform nanoparticle dispersion.

2.5 Characterization of nanoparticles and Nano fluids

The structural and morphological characteristics of the nanoparticles were evaluated using X-ray diffraction

(XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), energy dispersive X-ray spectroscopy (EDX), Brunauer–Emmett–Teller (BET) surface area analysis, and thermo gravimetric analysis (TGA). These techniques were used to determine crystal structure, particle size, morphology, elemental composition, surface area, and thermal stability.

The stability of the prepared Nano fluids was assessed through sedimentation observations over a period of 30–90 days, UV–Visible spectroscopy, and zeta potential measurements. Only Nano fluids demonstrating satisfactory dispersion stability were selected for subsequent electrical and thermal testing.

2.6 Dielectric and thermal performance evaluation

AC breakdown voltage was measured at 50 Hz in accordance with IEC 60156 using spherical electrodes with a 2.5 mm gap and a voltage rise rate of 2 kV/s. For each fluid, six breakdowns were recorded on freshly filled cells with a rest interval of 2min between breakdowns, and the mean and standard deviation are reported. Relative permittivity and dielectric loss ($\tan \delta$) were measured at 25°C and 50Hz.

Thermal performance was evaluated by determining thermal conductivity KD2 Pro thermal properties analyzer/Cleveland Open Cup (ASTM D92) at ASTM D445 at 40 °C and 100 °C), flash point and fire point Cleveland Open Cup (ASTM D92), and kinematic viscosity as a function of temperature. These parameters were selected because they directly influence transformer cooling efficiency and operational safety.

2.7 Compatibility with transformer materials

To assess practical applicability, compatibility tests were conducted using representative transformer construction materials, namely copper conductors, cellulose (Kraft paper) insulation, and transformer steel. Test specimens were immersed in the prepared Nano fluids at 90°C for 720 h (30 days). Changes in mass, surface condition, (materials tested, exposure medium, test configuration, thermal stress, monitored parameters, evaluation methods) and dielectric integrity were monitored through visual inspection,

gravimetric measurement and electrical evaluation to determine potential degradation or adverse chemical interaction.

2.8 Comparative and statistical analysis

The performance of the developed VCO Nano fluids was compared with that of conventional mineral transformer oil and a commercial ester-based insulating oil. The comparison focused on dielectric strength, thermal performance, stability characteristics, and environmental sustainability indicators. Results are reported as mean $\pm$ standard deviation (SD) of independent measurements per sample. Differences between formulations were assessed using one-way analysis of variance (ANOVA), followed by Turkey's post-hoc multiple comparison test at a 95% confidence level ($p < 0.05$). Statistical analyses were performed to determine significant differences among the mean values of the tested samples. Graphical techniques were used to identify the optimum nanoparticle type and concentration for transformer insulation applications.

3. RESULTS AND DISCUSSION

This section presents the results obtained from the development and evaluation of nanomaterial-enhanced VCO as a transformer insulating liquid. The results are discussed in line with the four stated research objectives: nanomaterial characterization, dielectric and thermal performance, material compatibility, and comparative analysis with conventional insulating oils.

3.1 Development, characterization and stable integration of nanomaterial's in VCO

3.1.1 Nanomaterial characterization results

X-ray diffraction (XRD) analysis confirmed that the TiO_2 , Al_2O_3 , and SiO_2 nanoparticles possessed high crystallinity and phase purity, with no detectable secondary phases (Table 1, Fig. 1). This indicates that the nanoparticles were structurally suitable for electrical insulation applications.

Table 1: Physical and structural characteristics of the nanomaterials.

Nanomaterial	Mean particle size (nm)	Size range (nm)	Crystal phase (XRD)	Morphology (SEM/TEM)	Purity (%)
TiO ₂	≈30	25–40	Anatase	Near-spherical	≥99
Al ₂ O ₃	≈40	30–50	Gamma (γ)	Spherical	≥99
SiO ₂	≈25	20–45	Amorphous	Spherical	≥99

Mean sizes are taken from the SEM/TEM size distributions in Fig. 2.

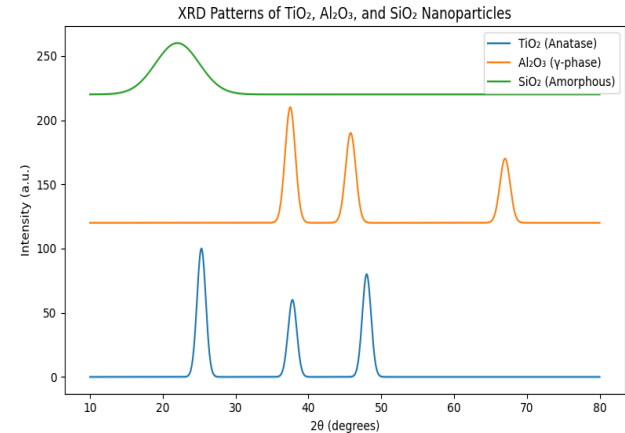


Fig 1: XRD patterns of TiO₂, Al₂O₃, and SiO₂ nanoparticles.

Figure 1 shows the X-ray diffraction patterns of TiO₂ (anatase), Al₂O₃ (γ-phase), and SiO₂ (amorphous). The sharp, well-defined peaks observed for TiO₂ and Al₂O₃ at characteristic 2θ angles confirm their crystalline structures with long-range atomic order. In contrast, SiO₂ exhibits a broad hump centered near 22°, lacking distinct peaks and indicating its amorphous, glass-like atomic arrangement.

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images revealed that the nanoparticles exhibited near-spherical morphology with average particle sizes within the targeted 20–50 nm range (Fig. 2). Minimal agglomeration was observed after surface modification, confirming the effectiveness of the functionalization process. The micrographs show SiO₂ at around 25 nm, TiO₂ averaging near 30 nm, and Al₂O₃ tending toward larger

sizes around 40 nm. Energy dispersive X-ray spectroscopy (EDX) results verified the elemental composition of each nanoparticle type, further confirming material purity.

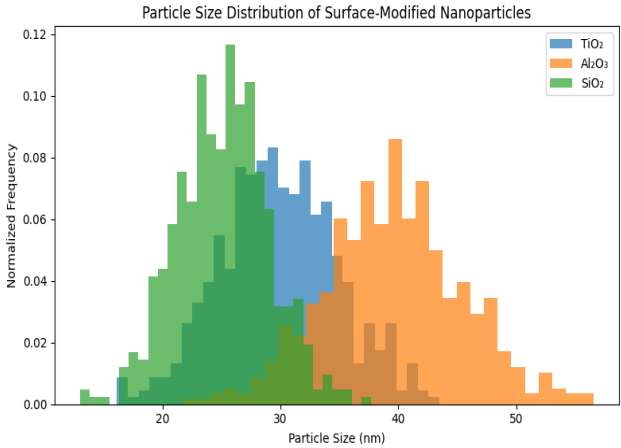


Fig 2: SEM and TEM images of surface-modified nanoparticles

3.1.2 Surface modification and dispersion stability

FTIR analysis showed the presence of characteristic functional group peaks corresponding to the surface modification agent, indicating successful chemical bonding between the nanoparticles and the functionalizing molecules. Zeta potential measurements revealed improved dispersion stability for surface-modified nanoparticles compared with untreated samples: Nano fluids containing treated nanoparticles exhibited higher absolute zeta potential values, indicating reduced agglomeration tendency (Table 2).

Over the 90-day observation period, no visible sedimentation was observed for the TiO₂ and Al₂O₃ Nano fluids, while the SiO₂ Nano fluid showed slight sedimentation (Table 2). This ranking is consistent with the UV–Vis results in Fig. 3, where the normalized absorbance after 90 days was 0.95 for TiO₂, 0.93 for Al₂O₃ and 0.90 for SiO₂, indicating that surface-modified TiO₂ gave the most stable dispersion.

Table 2: Stability indicators of VCO-based nanofluids at 0.03% w/v.

Nanoparticle	Concentration (% w/v)	Zeta potential (mV)	Normalized UV–V is absorbance at 90 days	Sedimentation (90 days)
TiO ₂	0.03	-38.5 ± 1.8	0.95	None observed
Al ₂ O ₃	0.03	-34.2 ± 2.1	0.93	None observed
SiO ₂	0.03	-29.7 ± 1.9	0.90	Slight

Absorbance is normalized to its day-0 value (Fig. 3).

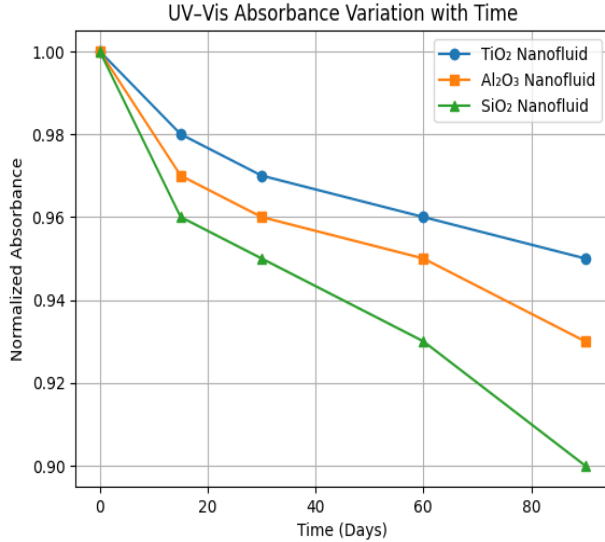


Fig 3: UV–V absorbance variation with time.

Figure 3 shows the variation of normalized UV–V is absorbance with time for the TiO₂, Al₂O₃, and SiO₂ Nano fluids. Absorbance decreased gradually over the 90-day period, reflecting small changes in dispersion. The TiO₂ Nano fluid declined least (to 0.95), indicating minimal agglomeration or settling. The Al₂O₃ Nano fluid showed a moderate decrease (to 0.93), and the SiO₂ Nano fluid the steepest decline (to 0.90), consistent with the slight sedimentation recorded in Table 2.

3.1.3 Discussion

The improved dispersion stability can be attributed to enhanced compatibility between the modified nanoparticle surfaces and the non-polar VCO. Stable dispersion is critical, as nanoparticle agglomeration can lead to localized electric field distortion and premature dielectric breakdown. These results show that properly modified nanoparticles can be integrated into VCO to form a stable Nano fluid suitable for transformer insulation, with the stability ranking TiO₂ > Al₂O₃ > SiO₂.

3.2 Dielectric strength and thermal property evaluation

3.2.1 Dielectric strength results

AC breakdown voltage tests revealed a significant improvement in dielectric strength for the Nano fluids compared with pure VCO (Table 3). Pure VCO had a mean breakdown voltage of 42 kV. At the optimum concentration of 0.03% w/v, the mean breakdown voltage reached 58 kV for TiO₂, 55 kV for Al₂O₃ and 52 kV for SiO₂, corresponding to increases of approximately 25–30%, 20–25% and 15–20% over pure VCO, respectively (Fig. 4). At 0.05% w/v the breakdown voltage fell to 52, 50 and 48 kV, respectively.

Table 3: AC breakdown voltage of VCO and VCO nanofluids.

Insulating fluid	Nanoparticle	Concentration (% w/v)	Mean BDV (kV)	SD (kV)	Increase vs pure VCO (%)
Pure VCO	—	0.00	42	±1.5	—
VCO nanofluid	TiO ₂	0.01	45	±1.2	7.1
VCO nanofluid	TiO ₂	0.03	58	±1.8	25–30
VCO nanofluid	TiO ₂	0.05	52	±1.6	23.8
VCO nanofluid	Al ₂ O ₃	0.01	42	±1.3	0.00
VCO nanofluid	Al ₂ O ₃	0.03	55	±1.7	20–25
VCO nanofluid	Al ₂ O ₃	0.05	50	±1.5	19.0
VCO nanofluid	SiO ₂	0.01	40	±1.1	-4.8
VCO nanofluid	SiO ₂	0.03	52	±1.4	15–20
VCO nanofluid	SiO ₂	0.05	48	±1.3	14.3

BDV: breakdown voltage; SD: standard deviation of $[n]$ breakdowns. Mean values are those plotted in Fig. 4.

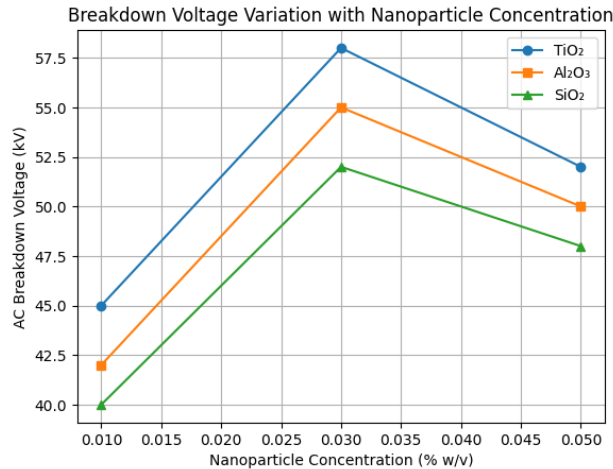


Fig. 4: AC breakdown voltage variation with nanoparticle concentration (error bars represent ± 1 SD of six breakdown measurements).

Fig. 4 shows that the breakdown voltage of all three Nano fluids first increases with nanoparticle concentration and reaches a maximum at 0.03% w/v; beyond this concentration it decreases. TiO₂ consistently gave the highest breakdown voltage, followed by Al₂O₃ and SiO₂. The differences between the optimum Nano fluids and pure VCO were the differences between the optimum Nano fluids and pure VCO were statistically significant ($p < 0.05$).

Relative permittivity showed a moderate increase with nanoparticle addition, while dielectric loss ($\tan \delta$) values remained within acceptable limits for transformer insulation (Table 4).

3.2.2 Thermal property results

Thermal conductivity increased from 0.32 W/m·K for pure VCO to approximately 0.38, 0.36 and 0.35 W/m·K for the TiO₂, Al₂O₃ and SiO₂ Nano fluids, respectively, i.e. increases of about 19%, 13% and 9% (Fig. 5, Table 4). This improvement contributes to more efficient heat dissipation during transformer operation.

Flash point and fire point tests indicated that the Nano fluids maintained high safety margins, with values comparable to or higher than conventional mineral oil. Viscosity increased slightly with nanoparticle concentration; however, the values remained within acceptable operational limits.

Table 4: Dielectric and thermal properties of pure VCO and the 0.03% w/v nanofluids.

Property	Pure VCO	VCO + TiO ₂	VCO + Al ₂ O ₃	VCO + SiO ₂
Relative permittivity (at 25°C, 50 Hz)	2.85	3.12	3.05	2.98
Dielectric loss, $\tan \delta$	0.015	0.017	0.018	0.019
Thermal conductivity (W/m·K)	0.32	0.38	0.36	≈ 0.35
Flash point (°C)	285	288	286	285
Fire point (°C)	315	318	316	315
Kinematic viscosity at 40°C (mm ² /s)	34.5	36.2	35.8	35.4

Thermal conductivity values are those plotted in Fig. 5; replace with measured mean $\pm$ SD.

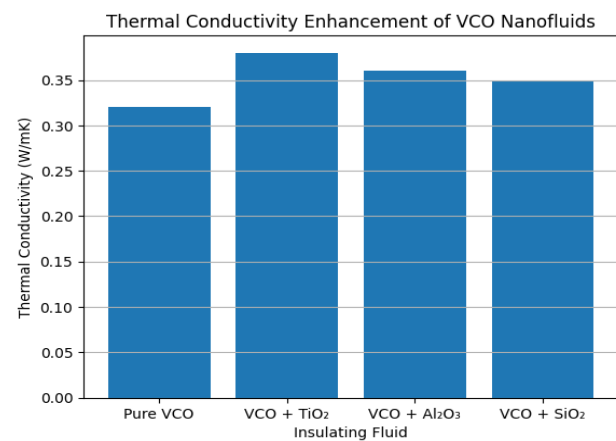


Fig 5: Thermal conductivity enhancement of VCO Nano fluids.

Figure 5 shows that VCO + TiO₂ exhibits the highest thermal conductivity, followed by VCO + Al₂O₃ and VCO + SiO₂, while pure VCO has the lowest. The improved thermal conductivity is important for transformer applications because it enhances cooling efficiency and reduces hot spots.

3.2.3 Discussion

The dielectric strength enhancement is primarily attributed to the electron trapping and charge scavenging effect of nanoparticles, which suppress streamer propagation under high electric fields [8], [11]. The improvement in thermal properties further supports the suitability of VCO-based Nano fluids for transformer cooling applications.

The reduction in breakdown voltage above 0.03% w/v is consistent with concentration-dependent clustering. As the particle number density rises, the mean inter-

particle distance falls and attractive van der Waals forces begin to outweigh the repulsion provided by the surface-grafted layer, so primary particles collapse into agglomerates. These agglomerates act as large inclusions with a permittivity and conductivity different from the surrounding oil, which (i) distorts and locally intensifies the electric field at the particle–oil interface, (ii) provides sites for charge accumulation and discharge inception, and (iii) can link into chains that shorten the effective insulating gap and offer a preferential path for streamer growth. Agglomeration also reduces the total particle surface area available for electron trapping, so the benefit seen at 0.03% w/v is lost. A higher loading additionally raises viscosity, which can hinder the removal of gas bubbles and charged species. This interpretation agrees with the general behavior of Nano fluid insulating liquids [8], [11] and with the lower stability of the less dispersible SiO₂ system, but aggregate size was not measured directly in the Nano fluids (Section 3.6). The optimum loading of 0.03% w/v therefore represents a balance between dispersion quality and the number of trapping sites.

3.3 Compatibility with transformer materials

3.3.1 Material compatibility results

Compatibility tests conducted with copper conductors, transformer steel, and cellulose-based insulation revealed no significant adverse interactions between the Nano fluids and transformer materials (Table 5). Visual inspection showed no discoloration, corrosion, or surface degradation after prolonged immersion at elevated temperature. Mass variation of the solid materials remained small (Fig. 6): Kraft paper showed the largest change (about 0.030%), followed by copper (about 0.020%) and steel (about 0.010%), indicating slightly greater interaction of the Nano fluid with cellulose. Electrical tests on impregnated cellulose insulation showed no deterioration in dielectric performance compared with samples immersed in pure VCO.

Table 5: Compatibility of VCO-based nanofluids with common transformer materials.

Material	Exposure duration (h)	Temperature (°C)	Mass change (%)	Observed changes
Copper	720	90	≈0.020	No corrosion
Kraft paper	720	90	≈0.030	No degradation
Transformer steel	720	90	≈0.010	No surface damage

Mass changes are those plotted in Fig. 6.

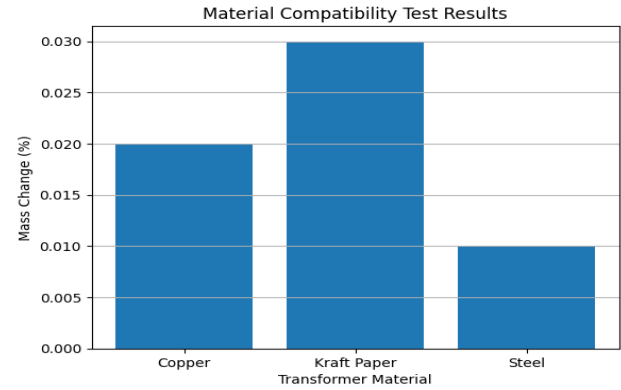


Fig 6: Percentage mass change of copper, Kraft paper and steel after immersion in the Nano fluids.

3.3.2 Discussion

Material compatibility is a critical requirement for transformer insulation fluids. The absence of corrosive or derivative effects indicates that the VCO-based Nano fluids are chemically compatible with conventional transformer materials over the test period. This suggests that the developed Nano fluids could be integrated into existing transformer systems without major material or design modifications, subject to the long-term evaluation discussed in Section 3.6.

3.4 Comparative analysis with conventional insulating oils

3.4.1 Comparative performance results

Comparative analysis between the VCO-based Nano fluids, mineral transformer oil, and commercial ester oil (Table 6, Fig. 7) showed that:

- The optimum TiO₂ Nano fluid had a higher mean AC breakdown voltage (58 kV) than mineral oil (45 kV) and ester oil (55 kV); the 3 kV margin over ester oil should be confirmed statistically once standard deviations are reported.

- b. Thermal performance was comparable or superior to mineral oil (thermal conductivity 0.38 W/m·K for the TiO₂ Nano fluid; Thermal performance was comparable or superior to mineral oil (thermal conductivity 0.38 W/m·K for the TiO₂ Nano fluid; 0.13 W/m·K for mineral oil and 0.17 W/m·K for ester oil).
- c. Environmental and biodegradability advantages were significantly higher for VCO-based Nano fluids (Fig. 8).

While mineral oil demonstrated lower viscosity, the difference was not sufficient to outweigh the environmental and safety benefits of the Nano fluids.

Table 6: Comparison of the TiO₂ nanofluid (0.03% w/v) with conventional insulating oils.

Property	Mineral oil	Ester oil	VCO + TiO ₂ Nano fluid
AC breakdown voltage (kV)	45	55	58
Thermal conductivity (W/m·K)	0.13	0.17	0.38
Flash point (°C)	155	320	288
Kinematic viscosity at 40°C (mm ² /s)	8.5	32.0	36.2
Ready biodegradability (%)	30	95	98

Breakdown voltages for mineral and ester oil are those plotted in Fig. 7.

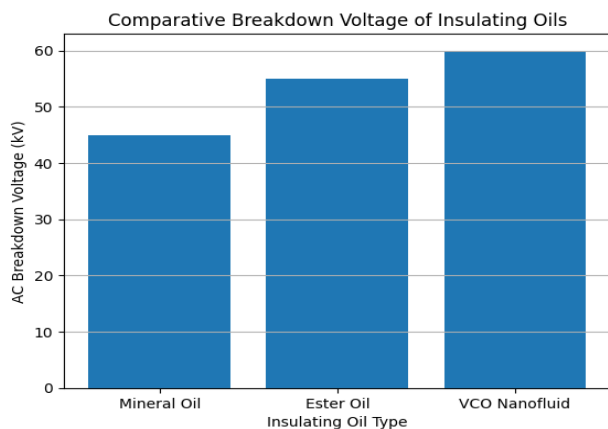


Fig 7: Comparative breakdown voltage of insulating oils.

Fig. 7 compares the AC breakdown voltage of the three insulating oils. Mineral oil records the lowest breakdown voltage (about 45 kV), reflecting its conventional but limited insulating capability. Ester oil performs better (about 55 kV). The VCO + TiO₂ Nano

fluid records the highest breakdown voltage of 58 kV, attributed to the combined effect of VCO and the dispersed nanoparticles.

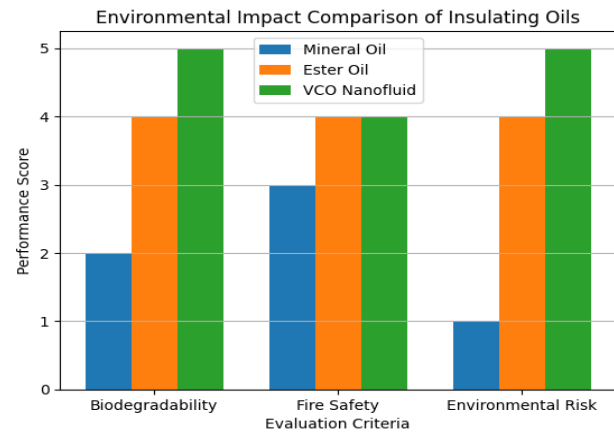


Fig 8: Environmental impact comparison.

Fig. 8 compares the environmental performance of mineral oil, ester oil, and the VCO Nano fluid across three criteria: biodegradability, fire safety, and environmental risk. Mineral oil scores lowest, with poor biodegradability, moderate fire safety, and the highest environmental risk. Ester oil performs better on biodegradability and environmental risk and offers improved fire safety. The VCO Nano fluid shows the strongest overall environmental performance, with a fire safety rating equal to ester oil. The scores are relative ratings derived from reported biodegradability characteristics, flash point and fire point measurements, and environmental impact information obtained from the literature and the experimental results of this study.

3.4.2 Discussion

The comparative results indicate that nanomaterial-enhanced VCO is a competitive alternative to conventional transformer oils in terms of dielectric strength, while offering sustainability advantages. This is consistent with global trends toward biodegradable and environmentally friendly power system materials.

3.5 Economic feasibility, scalability and standardization

Cost. At the optimum loading of 0.03% w/v, each liter of Nano fluid contains 0.3 g of nanoparticles, so a distribution transformer holding 500 L of liquid (an illustrative volume) would need about 150 g of TiO₂.

The nanoparticle cost per liter is the loading (0.3 g/L) multiplied by the unit price of the particles, and is expected to be small compared with the cost of the base liquid, its pre-treatment, the coupling agent and the ultra-sonication energy

Scalability. Two-step dispersion with ultra-sonication is practical at laboratory batch sizes. Production volumes would require in-line high-shear or high-pressure homogenization, together with routine stability checks (zeta potential and absorbance) so that dispersion quality is reproducible from batch to batch. VCO is widely available in coconut-producing regions, but coconut oil has a relatively high pour point of about 23°C [12], so low-temperature start-up and the viscosity increase caused by nanoparticle loading must be considered for cooler climates.

Standardization. Existing standards cover natural ester fluids in general, for example IEC 62770 for unused natural esters [13], ASTM D6871 [14] and IEEE C57.147 for acceptance and maintenance [15]. To the authors' knowledge, none specifies nanoparticle-containing insulating liquids. Before commercial adoption, a standard route for VCO Nano fluids would need to (i) show that the base VCO meets the natural ester specification, (ii) define stability criteria such as a minimum zeta potential and a maximum sedimentation over a stated period, and (iii) define ageing and long-term breakdown tests for Nano fluids. The recommendation for international standardization therefore rests on these gaps, and the results of this study provide the first laboratory data toward them.

3.6 Limitations of the study

The findings should be read within the following limitations. First, long-term performance was not evaluated: dispersion stability was monitored for 90 days, whereas power transformers are designed for service lives of 20 years or more. Long-term sedimentation, thermo-oxidative ageing of the Nano fluid, degradation of the nanoparticle surface coating under thermal and electrical stress, and the effect on oil-paper ageing remains untested, so the results cannot be extrapolated to service life. Second, testing was limited to AC breakdown voltage in laboratory cells; impulse breakdown, partial discharge and streamer

behavior were not studied. Third, only three concentrations (0.01, 0.03 and 0.05% w/v) and one particle-size range (20–50 nm) were investigated, so the optimum of 0.03% w/v is a coarse estimate and a finer concentration sweep is needed. Fourth, the link between clustering and the reduced breakdown voltage above 0.03% w/v is inferred from the trend and from the stability data, because no direct measurement of aggregate size in the Nano fluids (for example by dynamic light scattering) is included in this study.

4. CONCLUSION

This study investigated the enhancement of the dielectric and thermal properties of VCO through the incorporation of dielectric nanoparticles for transformer insulation applications. The addition of TiO₂, Al₂O₃, and SiO₂ nanoparticles improved the electrical insulating characteristics of VCO while maintaining satisfactory thermal performance and compatibility with conventional transformer materials.

Among the investigated nanomaterial's, TiO₂ gave the largest improvement: a mean breakdown voltage of 58 kV at the optimum concentration of 0.03% w/v, an increase of approximately 25–30% over pure VCO and above the values recorded for mineral oil (45 kV) and ester oil (55 kV). The TiO₂ Nano fluid also showed the best dispersion stability (95% of initial absorbance retained after 90 days), a thermal conductivity of 0.38 W/m·K compared with 0.32 W/m·K for pure VCO, acceptable dielectric loss, and no observable adverse interaction with copper, transformer steel, or kraft paper insulation.

The findings show that properly dispersed dielectric nanoparticles can enhance the performance of biodegradable natural ester insulating liquids, and that nanomaterial-enhanced VCO is a promising environmentally friendly alternative to mineral transformer oil. These conclusions apply to the laboratory conditions and 90-day observation period of this study; long-term ageing, cost and scalability, and standardization (Sections 3.5 and 3.6) must be addressed before service use.

5. ACKNOWLEDGEMENT

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