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Experimental investigation of palm oil methyl ester nanofluid as a liquid insulating material

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Abstract: This study evaluates Palm Oil Methyl Ester (POME) as a potential base fluid for transformer insulation, enhanced with Titanium Dioxide (TiO_2) nanoparticles. The research aims to assess the dielectric strength and physicochemical properties of TiO_2-POME nanofluids at two concentrations (0.05 g/L and 0.10 g/L) and compare them with pure POME. The breakdown voltage (BDV) test was conducted before and after thermal ageing to determine how the nanofluid's dielectric strength changes over time. Results showed that both nanofluid samples had higher BDV values than pure POME, with the 0.05 g/L sample increasing from 19.27 kV to 25.85 kV and the 0.10 g/L sample showing the most significant improvement, with a BDV of 33.17 kV. Ageing caused a slight decrease in BDV, but the values remained higher than those of the base fluid (15.40 kV for aged pure POME), with the 0.05 g/L and 0.10 g/L samples maintaining averages of 20.68 kV and 24.44 kV, respectively, suggesting improved insulation performance. The kinematic viscosity of pure POME was 8.85 cSt, while the 0.05 g/L and 0.10 g/L TiO_2 nanofluids showed values of 9.09 cSt and 9.52 cSt, respectively, with all the samples falling within the acceptable range of 3-12 cSt specified by IEC 60296 for transformer insulating oils. The addition of TiO_2 slightly increased viscosity, more noticeably at 0.10 g/L. FTIR analysis indicated that the chemical structure of the fluid remained stable after ageing and nanoparticle addition.

Keywords: AC breakdown voltage; FTIR spectra; nanofluid; palm oil methyl ester; physicochemical properties

1. Introduction

The exploration of Palm Oil (PO) as a nanofluid for dielectric insulation offers a promising avenue to enhance electrical insulation properties across various applications, particularly in power utilities. Palm oil methyl ester (POME), a byproduct of palm oil production, has garnered attention for its unique physicochemical properties and its potential for modification through nanotechnology. The dielectric characteristics of nanofluids, which are suspensions of nanoparticles in a base fluid, can be significantly enhanced by incorporating various nanoparticles, thereby improving their thermal and electrical performance [1], [2], [3], [4], [5], [6].

Research indicates that POME can achieve breakdown voltages exceeding 60 kV, which is significantly higher than conventional dielectric fluids. This improvement is attributed to reduced viscosity and enhanced dielectric properties resulting from the formation of nanofluids. The integration of nanoparticles, such as TiO_2, into POME warrants further exploration to enhance its thermal and electrical properties. TiO_2-based POME nanofluids have demonstrated improved thermal conductivity and rheological properties, making them suitable candidates for heat transfer applications. Studies have shown that adding nanoparticles can significantly improve the AC breakdown voltage of insulating liquids, thereby enhancing their performance in electrical applications. This interfacial zone plays a vital role in preventing agglomeration and ensuring uniform distribution of nanoparticles, which is essential for achieving optimal electrical performance [7], [8], [9], [10], [11], [12].

Despite the widespread use of mineral oil in transformers, its environmental impact and non-renewable nature pose significant challenges. Mineral oil is derived from petroleum, a finite resource, and its spillage or leakage can lead to severe environmental contamination. Additionally, disposing of mineral oil is costly and complex because it does not degrade easily. Vegetable oils, such as palm oil (PO), have been proposed as alternatives due to their biodegradability and renewability. However, vegetable oils often exhibit higher viscosity and lower thermal stability compared to mineral oil, which can affect the cooling efficiency of transformers.

Recent studies have demonstrated enhanced thermal and physical properties of vegetable-oil- and bio-based nanofluids, positioning them as sustainable alternatives for industrial applications [13]. For example, [7] showed that MXene-POME nanofluids significantly improved heat transfer. Beyond thermal conductivity, the integration of eco-friendly additives has been proven to optimize fluid stability and mechanical performance. For instance, the addition of carboxymethyl cellulose and plant extracts has successfully yielded novel anti-corrosion properties and improved tribological performance in water-based lubricants [14]. Similarly, reviews on cellulose-based additives emphasize their ability to form protective boundary layers and enhance load-bearing capacity in biodegradable systems [14], while related studies highlight how nanoparticle dispersion impacts the viscosity and stability of polyol ester-based biolubricants [15]. While these findings demonstrate that nanoparticle type, concentration, and base fluid properties profoundly enhance mechanical and thermal profiles, their specific impact on the electrical properties of natural esters requires targeted investigation.

To bridge this gap, the main objective of this study is to evaluate the electrical and physicochemical properties of the POME nanofluid as a liquid dielectric insulation material. The specific objectives include analyzing the breakdown voltage of low-concentration TiO_2 POME-nanofluids (0.05 g/L and 0.10 g/L) before and after thermal ageing to assess dielectric strength and stability, investigating the physicochemical properties including kinematic viscosity and FTIR, and comparing the performance against pure POME to comprehensively determine its suitability as a transformer insulation material. Unlike prior studies that often focus on different base oils or lack long-term degradation tracking, the novelty of this work lies in evaluating TiO_2-POME nanofluids at specifically optimized low concentrations (0.05 g/L and 0.10 g/L). This study provides an integrated assessment combining AC breakdown voltage testing before and after thermal ageing, Weibull statistical analysis, and comprehensive physicochemical characterization (FTIR, density, and viscosity). This integrated approach provides new quantitative insights into the dielectric performance and stability of TiO_2-modified POME under operational thermal stress.

2. Material and methods

Palm Oil (PO) can be converted into a POME nanofluid by dispersing nanoparticles in treated POME, thereby enhancing its electrical and physicochemical properties. Initially, POME is treated to remove impurities [16]. In the present study, nanofluid stability was ensured through a carefully controlled dispersion process using Cetyltrimethylammonium bromide (Figure 1) as a surfactant in a 1:2 mass ratio with TiO_2 (0.01g CTAB to 0.02g TiO_2) [17]. The 1000 ml POME and CTAB mixture was initially magnetically stirred at 1200 rpm for 30 minutes, followed by an additional 1 hour at 1200 rpm after the addition of the nanoparticles to ensure uniform dispersion. To further break down agglomerates and achieve true homogeneity, the mixture underwent high-energy probe sonication (40 kHz, 300 W) for 2 hours at a controlled temperature of 50°C, with 30-minute intervals and 10-minute breaks to avoid overheating. Finally, the fluid was oven-dried for 48 hours at 85°C with the lid open to minimize residual moisture. This rigorous preparation process significantly improves the nanofluid's dielectric strength, thermal conductivity, and viscosity, making it a promising eco-friendly dielectric insulation material for industrial applications, as depicted in Figure 1 [18].

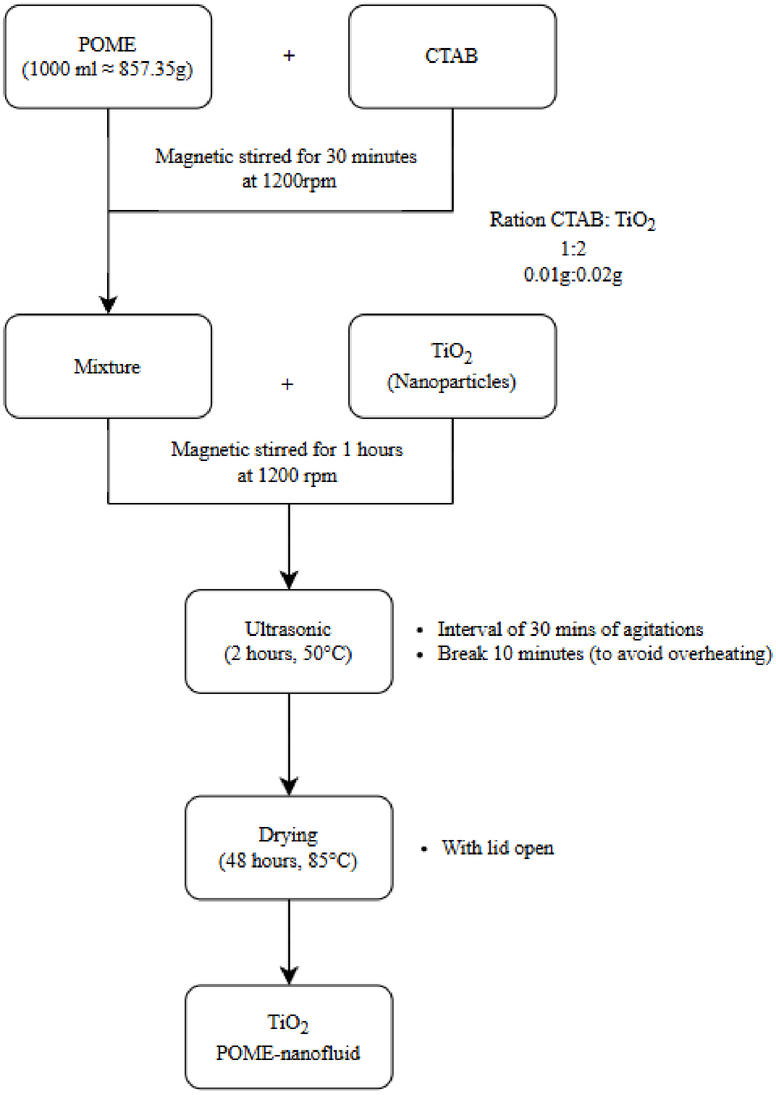


Figure 1. Development process of POME-based Hybrid Nanofluid

Although zeta potential, particle size distribution, and extended sedimentation tests with photographic evidence were not performed, the extremely narrow density variations across samples (<0.0002 g/cm^3), the statistical consistency of the breakdown voltage values (maintaining normal distribution with p-values > 0.05), and the uniform FTIR spectra collectively confirm that the nanoparticles remained stably dispersed without significant agglomeration. Future work will include quantitative stability analysis such as zeta potential measurements and sedimentation studies over extended periods to further validate these findings.

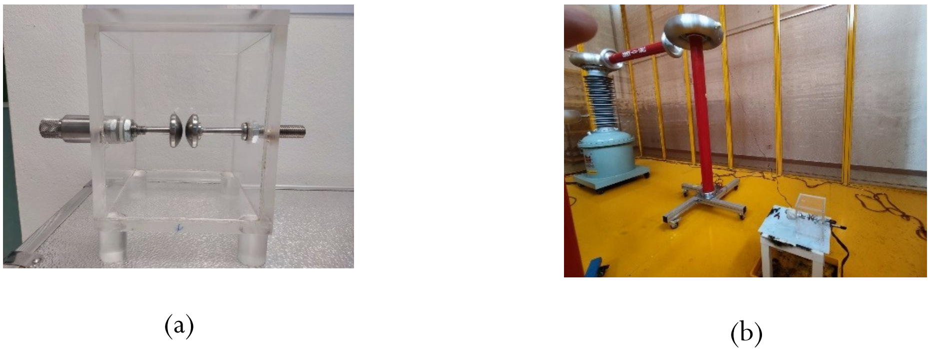
2.1 Accelerated thermal ageing test

Accelerated thermal ageing was conducted to simulate the long-term operating conditions of a transformer. The TiO_2 POME-nanofluid is subjected to elevated temperatures over an extended period to evaluate its stability, dielectric properties, and thermal performance under stress. This process helps assess the nanofluid's durability and effectiveness as a dielectric insulation material, ensuring its reliability and suitability for real-world applications in high-temperature environments [19] [20]. The accelerated ageing of the oil samples using a thermal oven is shown in Figure 2.

Figure 2. POME-Nanofluid samples undergoing accelerated ageing in a thermal oven

2.2 AC Breakdown voltage (AC BDV) test

The breakdown voltage test was conducted at the UNIMAS High Voltage AC Laboratory using a spherical-electrode test cell to evaluate the dielectric strength of the POME-nanofluid. This test measures the maximum voltage the nanofluid can withstand before electrical breakdown occurs, providing critical data on its insulation performance. A high breakdown voltage indicates a superior dielectric performance, ensuring the nanofluid's reliability and effectiveness as an insulation material in high-voltage applications. The AC BDV test cell and the experimental setup are depicted in Figure 3.



(a) (b)

Figure 3. (a) Test cell for AC BDV measurement in accordance with IEC 60156, and (b) Experimental setup for the AC BDV test, showing the test cell, HV injection, electrical coil, mesh grounding, and platform

2.3 Physicochemical properties test

2.3.1 Density and viscosity test

Anton Paar DMA 35 Density Meter was used in this research to measure the density of oil samples. It is a portable, high-precision instrument used to measure the density of liquids. It operates by drawing a small sample (approximately 2 ml) into its measuring cell, where the density is determined using oscillating U-tube technology. The device automatically compensates for temperature variations, ensuring accurate and reliable results. The equipment provides critical data to assess their compatibility with standard transformer oils. Its ease of use, rapid measurements, and high accuracy make it ideal for evaluating the physicochemical properties of dielectric fluids.

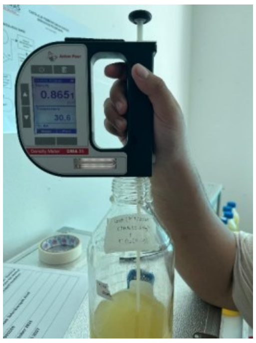


Figure 4. Density measurement of the oil samples using the Anton Paar DMA 35 handheld density meter

The IKA ROTAVISC lo-vi viscometer was used to measure the dynamic viscosity of POME and TiO_2 nanofluids at 40°C, ensuring compliance with IEC 60296 standards for transformer insulating liquids. This standard specifies acceptable viscosity ranges ($\leq 12\ mm^2/s$ at 40°C) to guarantee optimal fluid flow and heat dissipation in transformers. The picture of the equipment is shown in Figure 5.

Figure 5. Viscosity measurement of the oil samples using the IKA ROTAVISC lo-vi rotational viscometer

2.3.2 FTIR Spectra Test

Fourier Transform Infrared (FTIR) spectra analysis is conducted to examine the chemical structure and functional groups of POME and nanofluids using FTIR spectrometer (Shimadzu IRAffinity-1). A small amount of oil sample was placed on the crystal plate and scanned in the mid-infrared range (400–4000 cm^{-1}). This analysis ensures the chemical integrity of the samples and detects any changes due to nanoparticle addition or thermal ageing, validating their suitability as dielectric materials.

Figure 6. FTIR analysis of the oil samples using the Shimadzu IRAffinity-1 spectrophotometer

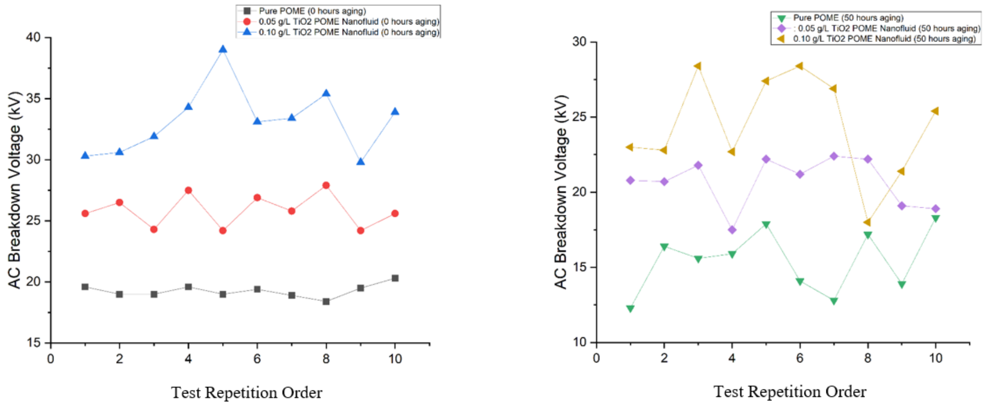
3. Results and discussion

3.1 Breakdown (AC BDV) voltage test

This study evaluated the AC BDV performance of POME-based nanofluids, a critical parameter for dielectric insulation applications. Figure 7 shows the AC BDV test results for the oil samples. Table 1 summarizes the normality test results for the AC BDV test of all oil samples. Pure POME demonstrated an initial average BDV of 19.27 kV, which decreased by 20% to 15.40 kV after 50 hours of thermal ageing as shown in Figure 7 and Table 1. This reduction reflects the natural degradation of ester-based fluids under prolonged thermal stress, likely due to oxidative processes and moisture absorption [9], [10], [21], [22]. Quantitatively, the 0.05 g/L TiO_2 nanofluid improved the base POME BDV from 19.27 kV to 25.85 kV (a 34% increase), while the 0.10 g/L concentration reached 33.17 kV (a substantial 72% increase based on mean BDV, equivalent to 72.7% on the Weibull U50 basis). Compared with previously reported vegetable-oil nanofluid systems, which typically achieve BDV enhancements of 20% to 40% at similar or higher nanoparticle loadings, this 72% improvement demonstrates highly competitive performance [23], [24]. Furthermore, after 50 hours of thermal ageing, the 0.10 g/L sample retained a BDV of 24.44 kV, which remains significantly higher than even the unaged pure POME (19.27 kV). These quantitative benchmarks confirm that the optimized low-concentration TiO_2-POME nanofluid is not only competitive with, but in terms of sustained dielectric strength, superior to many conventional ester-based insulating fluids reported in the current literature.

The enhancement in dielectric strength may be attributed to electron trapping at the nanoparticle-fluid interface [25]. TiO_2 nanoparticles provide additional interfacial regions where free electrons are captured, delaying streamer formation and electrical breakdown. Higher concentrations (0.10 g/L) create more charge-trapping sites, explaining the proportionally increased BDV observed. Furthermore, as supported by the FTIR spectra analysis (Figure 10), the stable physical interaction between the TiO_2 nanoparticles and the POME ester carbonyl groups (C=O stretch at 1739.79 cm^{-1}) creates a dense, localized interfacial zone. This interfacial volume acts as a physical and energetic barrier, restricting charge-carrier mobility and effectively slowing streamer propagation under high-voltage stress. This mechanism aligns with prior reports on nanoparticle-enhanced vegetable oil dielectric fluids, confirming that the synergy of electron trapping and stable ester-nanoparticle interactions fundamentally improves the fluid's insulation performance [26], [27].

Importantly, both nanofluid formulations showed superior ageing resistance compared to the pure POME, with the 0.10 g/L sample maintaining BDV values above unmodified POME even after thermal stress. While direct experimental comparison with commercial mineral oils was not performed in this study, established literature and industry standards provide a clear benchmark for evaluation. According to standard guidelines for new and untreated mineral insulating oils (such as IEC 60296 and tested via IEC 60156), the minimum acceptable breakdown voltage is typically ≥ 30 kV [28]. The optimized 0.10 g/L TiO_2-POME nanofluid achieved 33.17 kV before ageing, demonstrating highly competitive performance that surpasses this conventional baseline. Furthermore, the nanofluid's retention of 24.44 kV after 50 hours of thermal ageing suggests superior dielectric stability compared to many pure vegetable-based esters, which often struggle with rapid degradation under thermal stress. This confirms that the specific 0.10 g/L formulation is commercially viable and competitive with existing synthetic transformer fluids, while offering significant environmental benefits such as high biodegradability and renewability.



(a) 0 hour of ageing time (b) 50-hour of ageing time

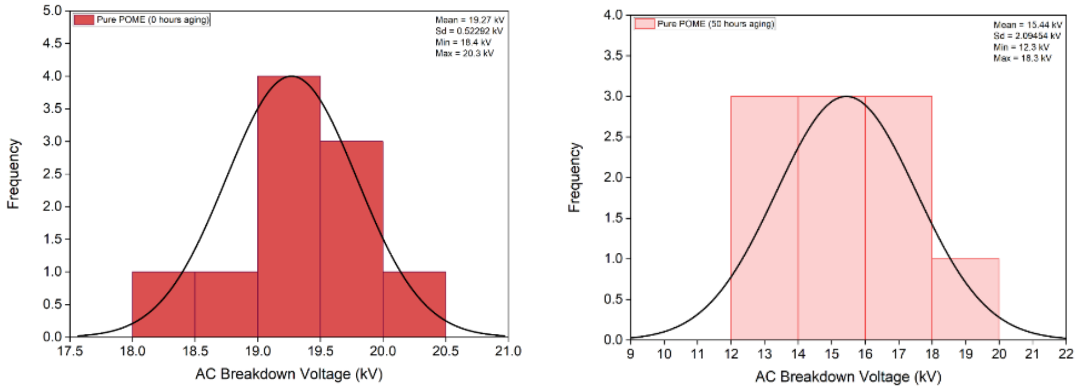
Figure 7. AC BDV test results of the oil samples

BDV data underwent rigorous statistical validation through normality testing (Table 1). Figure 8 shows the histogram of a normal distribution for oil samples. For pure POME, the Anderson-Darling test confirmed normal distribution in both unaged ($p=0.38583$) and aged ($p=0.77614$) conditions, as shown in Figure 8(a) and (b). While thermal ageing reduced mean BDV values, the data maintained normal distribution, indicating consistent degradation patterns across samples. The POME + 0.05 g/L TiO_2 nanofluid showed equally robust normality results, as shown in Figures 8 (c) and (d). Unaged samples yielded $p=0.46069$, while aged samples showed $p=0.19878$, confirming stable statistical properties despite the incorporation of nanoparticles. This consistency supports the reliability of TiO_2's dielectric enhancement effects. Similarly, POME + 0.10 g/L TiO_2 nanofluids demonstrated normal distribution ($p=0.41562$ unaged, $p=0.55984$ aged) as shown in Figure 8 (e) and (f). The maintained normality across all concentrations suggests predictable dielectric behavior, with nanoparticle interactions not introducing significant anomalies in the data.

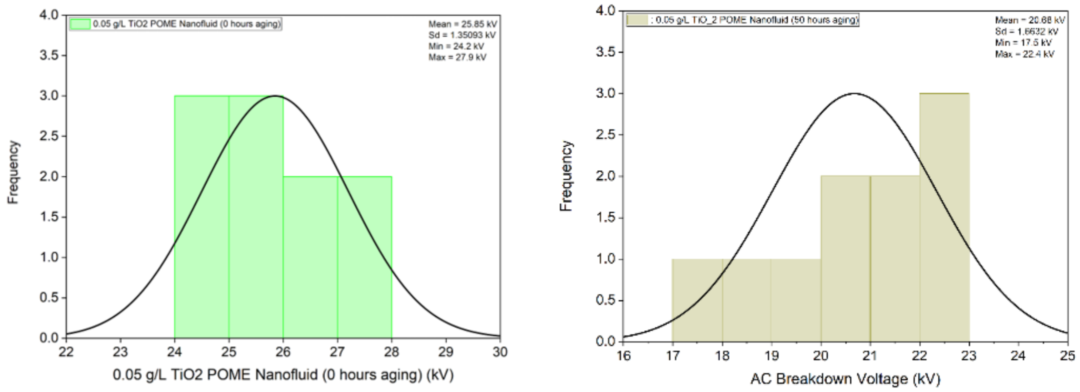
Table 1 shows the normality test result for the AC BDV test of all oil samples. All tested conditions had p-values > 0.05, as shown in Table 1, supporting the use of parametric statistical methods. This comprehensive normality confirmation reinforces the experimental reliability and enables meaningful comparison between different fluid formulations and ageing states. The consistent statistical behavior supports the conclusion that TiO_2 nanoparticles enhance dielectric performance without compromising measurement reliability.

Table 1. Normality test results for the AC BDV test of oil samples

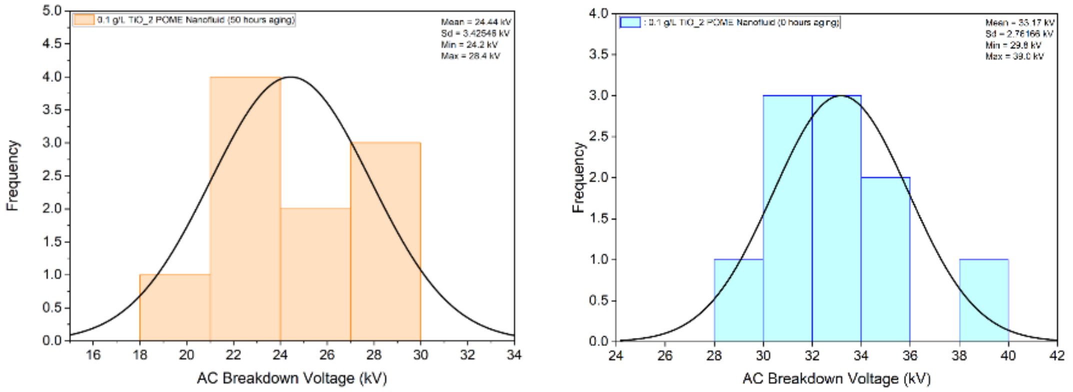
Oil samples	Statistic	p-values	Conformity to normal distribution
Pure POME 0-hour ageing	0.35388	0.38583	Accepted
Pure POME 50-hour ageing	0.21185	0.77614	Accepted
0.05 g/L TiO_2 0-hour ageing	0.32342	0.46069	Accepted
0.05 g/L TiO_2 50-hour ageing	0.46342	0.19878	Accepted
0.10 g/L TiO_2 0-hour ageing	0.34117	0.41562	Accepted
0.10 g/L TiO_2 50-hour ageing	0.28098	0.55984	Accepted



(a) Pure POME 0-hour ageing (b) Pure POME 50-hour ageing



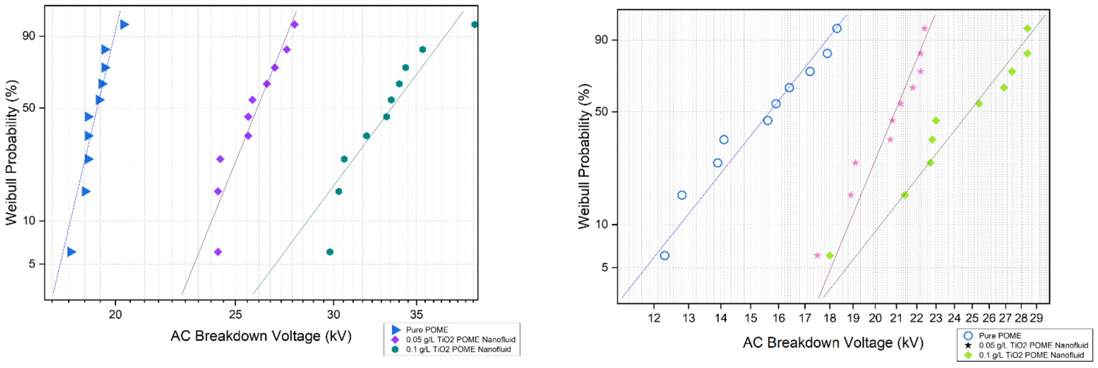
(c) POME + 0.05 g/L TiO_2 0-hour ageing (d) POME + 0.05 g/L TiO_2 50-hour ageing



(e) POME + 0.10 g/L TiO_2 0-hour ageing (f) POME + 0.10 g/L TiO_2 50-hour ageing

Figure 8. Histogram of the oil samples

Figures 9 (a) and (b) show the Weibull distribution of AC BDV for 0-hour aged oil samples. Weibull distribution modeling effectively characterized the breakdown behavior of POME-based nanofluids, as shown in the figures. Table 2 summarizes the Weibull distribution fit and p-values for all oil samples at the 0-hour ageing time. All samples showed excellent fit to the Weibull distribution ($p>0.05$), confirming the statistical reliability of the BDV data as shown in that table [29] [30].



(a) (b)

Figure 9. (a) Weibull distribution of AC BDV for 0-hour aged oil samples, and (b) Weibull distribution of AC BDV for 50-hour aged oil samples

Tables 2 and 3 show the Weibull percentile breakdown of voltages of all oil samples for 0-hour ageing time. Pure POME exhibited baseline dielectric strength with U50=19.309 kV. The POME + 0.05 g/L TiO_2 nanofluid showed a 34.8% improvement (U50=26.038 kV), while the 0.10 g/L concentration demonstrated a substantial 72.7% enhancement (U50=33.349 kV), as shown in Table 3. These improvements are attributed to TiO_2 nanoparticles acting as electron traps, effectively suppressing streamer formation.

Table 2. Weibull Distribution Fit and p-Values of Oil Samples for 0-hour ageing time

Ageing	Sample	p-Values	Conformity to Weibull distribution
0-hour	Pure POME	0.17323	Accepted
	$0.05\ g/L\ TiO_2$ POME Nanofluid	≥0.25	Accepted
	$0.10\ g/L\ TiO_2$ POME Nanofluid	0.2247	Accepted

Table 3. Weibull Percentile Breakdown Voltages of Oil Samples for 0-hour ageing time

Ageing	Sample	AC Breakdown Voltage (kV)			
		U1%	U10%	U50%	U63.2%
0-hour	Pure POME	17.216	17.996	19.309	19.567
	POME + 0.05 g/L TiO_2 Nanofluid	21.482	23.215	26.038	26.456
	POME + 0.10 g/L TiO_2 Nanofluid	23.412	26.911	33.349	34.462

Tables 4 and 5 show the Weibull percentile breakdown of voltages of all oil samples for a 50-hour ageing time. Weibull distribution modeling of 50-hour aged samples, as shown in Figure 9, confirmed that POME + TiO_2 nanofluids have superior dielectric stability compared to pure POME, as shown in Tables 4 and 5. All samples maintained Weibull conformity (p≥0.25), validating statistical reliability. Pure POME showed significant degradation (U50 = 15.671 kV, -19% relative to unaged). The 0.05 g/L TiO_2 nanofluid demonstrated better retention (U50=20.935 kV, -19.6%), while 0.10 g/L TiO_2 exhibited exceptional stability (U50=24.801 kV, only -25.6% decline).

Table 4. Weibull Distribution Fit and p-Values of Oil Samples for 50-hour ageing time

Ageing	Sample	p-Values	Conformity to Weibull Distribution
50 -hours	Pure POME	≥0.25	Accepted
	0.05 g/L TiO_2 POME Nanofluid	≥0.25	Accepted
	0.10 g/L TiO_2 POME Nanofluid	≥0.25	Accepted

Table 5. Weibull Percentile Breakdown Voltages of Oil Samples for 50-hour ageing time

Ageing	Sample	AC Break down Voltage (kV)			
		U1%	U10%	U50%	U63.2%
50-hours	Pure POME	9.788	11.786	15.671	16.365
	0.05 g/L TiO_2 POME Nanofluid	16.450	18.035	20.935	21.343
	0.10 g/L TiO_2 POME Nanofluid	15.531	18.677	24.801	25.833

Notably, aged 0.10 g/L TiO_2 nanofluid outperformed fresh pure POME (U50=19.309 kV), with its U10 value (18.677 kV) exceeding aged pure POME's U50. This demonstrates TiO_2's protective effect against thermal degradation, with higher concentrations providing greater preservation of dielectric strength through enhanced electron trapping and oxidation resistance [31]. Compared with previous studies on vegetable-oil-based nanofluids, the initial BDV improvements in TiO_2-POME nanofluids are consistent with general reports of enhanced dielectric performance due to charge-trapping effects. However, unlike prior studies that often utilize higher nanoparticle loadings, which can lead to agglomeration-induced premature breakdown and rapid oxidation, this work demonstrates the distinct performance advantage of a low-concentration approach. While many conventional ester-based nanofluids exhibit severe dielectric degradation under prolonged thermal stress, the optimized 0.10 g/L TiO_2-POME formulation maintained a highly competitive 24.44 kV even after 50 hours of ageing. This critical difference highlights that low-dose TiO_2 addition not only achieves a substantial 72% initial BDV improvement, but crucially mitigates the rapid dielectric deterioration typically observed in natural esters, providing deeper insight into sustaining long-term dielectric stability.

3.2 Physicochemical properties test

3.2.1 FTIR spectra

Figure 10 shows the Fourier Transform Infra-Red (FTIR) spectra for the oil samples. FTIR analysis indicated the successful integration of TiO_2 nanoparticles into POME while maintaining its chemical structure, as shown in the figure. Table 6 presents the interpretation of the FTIR Spectra of oil samples based on their wavenumbers. The spectrum showed characteristic ester peaks at 2927.94 cm^{-1} (C-H stretch), 1739.79 cm^{-1} (C=O stretch), and 1172.72 cm^{-1} (C-O stretch), indicating preservation of POME's molecular framework after nanoparticle addition, as shown in Table 6. The absence of new peaks confirmed that no chemical reactions occurred during nanofluid preparation. Key observations revealed nanoparticle-fluid interactions through subtle peak shifts, particularly in the carbonyl (C=O) region at 1739.79 cm^{-1}. These changes suggest TiO_2 particles formed physical bonds with POME's ester groups, promoting stable dispersion [32].

The consistent hydrocarbon peaks (2927.94 cm^{-1}) demonstrated that the nanoparticles did not disrupt POME's alkane backbone. The results suggest TiO_2 integrates well with POME through physical interactions rather than chemical modification. This maintains the fluid's base properties while enhancing dielectric performance through nanoparticle inclusion. The uniform dispersion indicated by FTIR correlates with the improved breakdown voltages measured in electrical properties tests.

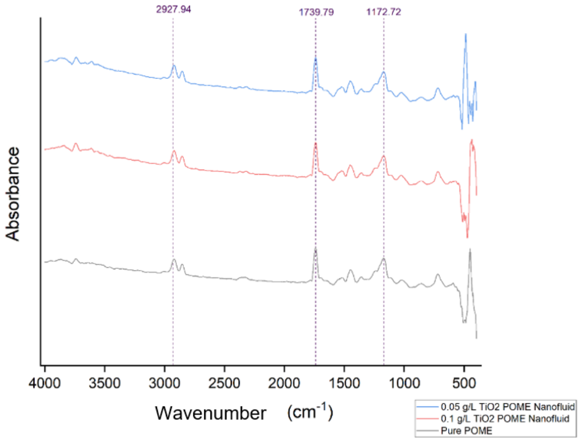


Figure 10. FTIR spectra of the oil samples

Table 6. Interpretation of FTIR spectra of oil samples

Type of POME	Area (cm^{-1})	Wavenumber (cm^{-1})	Functional Group
Pure POME 0.05 g/L TiO_2 0.10 g/L TiO_2	Region 1 (2500 – 4000)	2927.94	C – H stretch (alkanes)
Pure POME 0.05 g/L TiO_2 0.10 g/L TiO_2	Region 2 (2000 – 2500)	-	-
Pure POME 0.05 g/L TiO_2 0.10 g/L TiO_2	Region 3 (1500 – 2000)	1739.79	C = O stretch (esters)
Pure POME 0.05 g/L TiO_2 0.10 g/L TiO_2	Region 4 (500 – 1500)	1172.72	C – O stretch (esters)

3.2.2 Density and viscosity test

Density and dynamic viscosity measurement results are summarized in Table 7. It reveals that TiO_2 nanoparticles increase POME density in proportion to concentration while maintaining excellent uniformity. Pure POME showed consistent density (0.8648±0.0001 g/cm³), confirming measurement reliability. The 0.05 g/L TiO_2 nanofluid exhibited a slight density increase (0.8658±0.0001 g/cm³), while the 0.10 g/L concentration reached 0.8663 ± 0.0001 g/cm³. These minimal yet consistent changes (≤0.2% increase) demonstrate successful nanoparticle integration without compromising fluid homogeneity.

The narrow density ranges across all samples (<0.0002 g/cm³ variation) confirm excellent dispersion stability and batch-to-batch reproducibility which is critical for industrial dielectric fluid applications. These results validate TiO_2-POME nanofluids maintain the essential physical properties required for transformer applications while gaining enhanced dielectric performance. Dynamic viscosity analysis demonstrated that TiO_2 nanoparticles induce a concentration-dependent viscosity increase in POME while maintaining operational suitability. Pure POME showed baseline viscosity of 7.65 mPa·s, with TiO_2 additions causing modest rises to 7.87 mPa·s (+2.9%) at 0.05 g/L and 8.25 mPa·s (+7.8%) at 0.10 g/L. These increases reflect typical nanofluid behavior, where nanoparticle-fluid interactions create additional flow resistance. Importantly, all values remain within acceptable limits for dielectric applications, balancing improved nanoparticle suspension stability with maintained fluidity. The controlled viscosity changes support TiO_2-POME nanofluids as practical insulating fluids, offering enhanced dielectric properties without compromising essential flow characteristics for transformer applications. The proportional relationship between nanoparticle concentration and viscosity increase confirms predictable, manageable rheological modifications [33], [34].

Using Equation (1), the kinematic viscosity analysis of POME-based nanofluids containing TiO_2 nanoparticles revealed important insights into their flow behavior and practical applicability, which were subsequently included in Table 7 in column 3. Pure POME showed a baseline kinematic viscosity of 8.85 cSt, calculated from its measured dynamic viscosity of 7.65 mPa·s and density of 0.86478 g/cm³. This value falls within the expected range for natural ester-based insulating fluids and serves as a reference point for evaluating the effects of nanoparticles. The addition of TiO_2 nanoparticles at 0.05 g/L concentration resulted in a modest 2.7% increase in kinematic viscosity to 9.09 cSt, while the higher 0.10 g/L concentration produced a 7.6% increase to 9.52 cSt. These controlled viscosity changes demonstrate the predictable rheological modification achievable through nanoparticle loading.

$$v = \frac{\mu}{\rho} \tag{1}$$

where:

μ is the dynamic viscosity (measured in pascal-seconds, $Pa \cdot s$),
ρ is the fluid density (measured in kilograms per cubic meter, kg/m^3).

Table 7. Density and Viscosity of the Oil Samples

POME Sample	Dynamic Viscosity (mPa·s)	Density (g/cm³)	Kinematic Viscosity (cSt)
Pure POME	7.65	0.86478	8.85
POME + 0.05 g/L TiO_2	7.87	0.8658	9.09
POME + 0.10 g/L TiO_2	8.25	0.86634	9.52

All tested formulations maintained kinematic viscosity values below 10 cSt, well suited within the 12 cSt limit specified by IEC 60296 standard for transformer insulating fluids. The viscosity increases are attributed to enhanced particle-fluid interactions, which improve nanoparticle suspension stability without significantly altering flow characteristics. This balance is particularly important for transformer applications where both dielectric performance and efficient heat transfer are critical. The moderate viscosity enhancement benefits from reduced nanoparticle sedimentation rates, thereby promoting long-term stability of the nanofluid's enhanced dielectric properties [35].

4. Conclusion

The novelty of this work lies in proving that low-concentration TiO_2 additions (specifically 0.10 g/L) are sufficient to drastically improve POME's dielectric performance, validated through rigorous Weibull statistical analysis and physicochemical characterization (FTIR, density, and viscosity) before and after thermal ageing. This study suggests that TiO_2-enhanced POME nanofluids show potential as sustainable alternatives to mineral oils for transformer insulation. The 0.10 g/L TiO_2 concentration increased breakdown voltage by 72% while maintaining compliance with IEC 60296 viscosity standards (8.85-9.52 cSt at 40°C). FTIR confirmed nanoparticle integration without chemical degradation, and thermal ageing tests revealed excellent stability. The improved dielectric strength, coupled with enhanced flow characteristics and biodegradability, positions POME nanofluids as an eco-friendly solution for power infrastructure. These findings highlight the potential of nanotechnology to bridge performance and sustainability gaps in electrical insulation, warranting further development for commercial applications. Future research should focus on long-term stability and large-scale compatibility to facilitate industrial adoption.

Author's declaration

Author contribution

Yusri Jumat: conceptualization, validation, formal analysis, investigation, writing-original draft. **Yanuar Z. Arief**: funding acquisition, investigation, conceptualization, resources, writing - review & editing, supervision. **Hendri Masdi** and **Valentine M. A. A. Jabu**: writing - review & editing. **Sharifah M. W. Masra** and **Nurul I. Hashim**: investigation, data curation, methodology. **S. K. Sahari, N. Junaidi**, and **S. Rufus**: writing-original draft. **Hamzah Eteruddin** and **S. Wilyanti**: writing - review & editing.

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Data availability

The raw data supporting this study are available upon request. If anyone wishes to use it as a basis for further research, please contact the corresponding author.

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Competing interest

The authors declare no conflicts of interest regarding the present study.

Ethical clearance

Not applicable.

AI statement

The grammatical structure of this article was improved by using ChatGPT and Grammarly software, the authors have rechecked the accuracy and correctness of the generated sentences with the topic and data of this study. All data presented in this manuscript, including all figures, tables, and graphs, are derived from the authors' original experimental work and have not been previously published in any journal or publication. Furthermore, the authors certify that this article is a result of their original research and confirm that no sections of the text or visual elements were generated by Artificial Intelligence (AI).

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Nomenclature

AC BDV : Alternating Current Breakdown Voltage
FTIR : Fourier Transform Infrared
ν : Kinematic viscosity
μ : Dynamic viscosity
ρ : Fluid density
kV : kilo Volt
g/L : gram/liter
g/cm^3 : gram/centi meter cubic