International Journal of Technology 16(5) 1752-1771 (2025)

International Journal of Technology

http://ijtech.eng.ui.ac.id

Research Article

Comparative Study on the Performance of Ester Oil for Transformer Retrofilling

David Silalahi [1,4], Heri Hermansyah [1,2,*], Patrick Cognet [3]

[1] *Department of Chemical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia*
[2] *Research Center for Biomass Valorizations, Universitas Indonesia, Depok 16424, Indonesia*
[3] *Laboratoire de Génie Chimique, Université de Toulouse, CNRS, INPT, UPS, Toulouse, F-31432, France*
[4] *Western Java Transmission Main Unit, PT Perusahaan Listrik Negara (Persero), Depok 16514, Indonesia*
[*] *Corresponding author: heri.hermansyah@ui.ac.id; Tel: +62217863516*

Abstract: For long-term operation and sustainability, transformers require reliable and eco-friendly oil insulation. Although mineral oils have been used for over 150 years, their high fire risk, low biodegradability, and reliance on nonrenewable sources present challenges. This study aims to systematically evaluate the impact of aged mineral oil (AMO) contamination and fatty acid (FA) composition on the dielectric and physicochemical performance of synthetic (SEO) and natural ester oils (NEO) in transformer retrofilling applications. The novelty of this study lies in the detailed analysis of how varying AMO levels (7.5% and 9.5%) and FA profiles affect key properties—including breakdown voltage (BDV), moisture content, total acid number (TAN), viscosity, color index, and flash/fire points—under accelerated thermal aging at 135°C for 28 days. The results indicate that 9.5% AMO contamination increases BDV, color index, and TAN more significantly than 7.5%. The moisture content in the SEO remained within the IEC 61099 limits, whereas that in the NEO exceeded 200 ppm after 14 days. SEO with a lower C18:1 content (7.64%) demonstrated superior thermal stability compared to NEO, which exhibited higher oxidation susceptibility due to its higher C18:1 level (26.16%). High C18:1 levels reduced BDV, whereas AMO degraded heavy saturated fatty acids (C20–C24). Additionally, the increase in C12 in SEO reduced viscosity, potentially affecting oil flow. These findings clarify the role of FA composition and AMO contamination in optimizing transformer oil retrofilling strategies and support the future adoption of ester-based insulating liquids for more reliable and sustainable power systems.

Keywords: Competitiveness; Creative innovation; Digital infrastructure; Technology

1. Introduction

Electricity is a fundamental societal need that has become the backbone of economic development and social welfare. By 2015, Indonesia's electricity consumption had risen to 203 TWh from 134.5 TWh in 2008, with an estimated growth of approximately 6% annually (McNeil et al., 2019). PT PLN (Persero) is responsible for meeting national electricity needs and had operated transformers with a total capacity of 155,968 MVA by the end of 2021, a sharp increase from 98,897.5 MVA in 2016 (Erwantono et al., 2020). Transformers ensure reliable and efficient electricity supply in power transmission systems (Pramono et al., 2024). However, the increase in power demand poses operational challenges, especially the rise in transformer temperature, which accelerates insulation degradation and reduces the transformer life by up to 50% (Tokunaga et al.,

This research was funded by PT PLN (Persero) through the PBJJ Scholarship Program, under contract number 0786.Pj/SDM.07.02/F31000000/2023.

https://doi.org/10.14716/ijtech.v16i5.7707
Received March 2025; Revised May 2025; Accepted July 2025

2019; Ye et al., 2017). The degradation of the insulation system has resulted in faults (Dhini et al., 2020) and transformer failures of up to 75% of all high-voltage transformer failures, ultimately resulting in high transformer repair or replacement costs (Samikannu et al., 2022) and power outages (Siddique et al., 2024).

Mineral oil has served as a primary insulating fluid in transformers for over 150 years because of its excellent thermal properties, high efficiency, and cost-effectiveness (Abdul Hamid et al., 2022). Mineral oil helps reduce the risk of electrical faults, such as flashovers and sparkovers, and supports heat dissipation to prevent overheating due to its high dielectric strength and low electrical conductivity (Lyutikova et al., 2022). Mineral oil is a popular dielectric fluid; however, it poses a significant environmental hazard (Rafiq et al., 2020). With a low biodegradation rate of approximately 30% (Soni and Mehta, 2023), these oils are difficult to biodegrade and can contaminate soil and water. A leak or spill of 1 kg of mineral oil can contaminate up to 5 million liters of water (Karaman et al., 2023; Jacob et al., 2020; Rozga, 2013). In addition, mineral oil exhibits limited moisture tolerance, which can reduce its dielectric strength by up to 33% and cause current leakage in transformers (Jeong et al., 2024). With a flash point of approximately 130–140°C (Senthilkumar et al., 2021) and an ignition threshold near 170°C, petroleum-derived insulating liquids contribute to an increased risk of transformer fires (Hamid et al., 2021).

Ester-based oils have been suggested as a more sustainable alternative to mineral oil to address its drawbacks (Soni and Mehta, 2023). Ester-insulating oils are classified as either natural or synthetic based on their molecular structure and production process. Natural esters are primarily composed of triglyceride molecules, where three FA chains are esterified with the three hydroxyl groups of a single glycerol backbone (Kamhoua et al., 2024). This results in a dense network of polar ester bonds, which underlies their outstanding biodegradability—up to 97% (Mustangin et al., 2024)—and their pronounced polarity and hydrophilic character. The high polarity and the presence of multiple ester linkages allow NEO to absorb and dissolve a much larger amount of water than mineral oils—up to ten times more—because the ester bonds can interact with water molecules through dipole interactions and hydrogen bonding (Villarroel et al., 2021; Martin et al., 2013). Additionally, the molecular structure of both natural and synthetic esters—characterized by long-chain fatty acids and polar ester groups—accounts for their significantly higher flash and fire points compared to mineral oils. For instance, natural esters commonly have flash points exceeding 320°C and fire points above 360°C (Wang et al., 2023). However, this same chemical structure also renders natural esters more susceptible to hydrolysis and oxidative degradation, especially due to the presence of unsaturated fatty acids and the accessibility of ester bonds to water and oxygen, which can lead to acid formation and reduced oxidation stability (Raof et al., 2019). In contrast, synthetic ester oils are produced by esterifying fatty acids with polyol alcohols (such as pentaerythritol or trimethylolpropane), typically resulting in molecules with more uniform and branched structures. This molecular design introduces greater steric hindrance around the ester bonds, thereby limiting the number of reactive sites and enhancing the resistance to hydrolysis and oxidative degradation. Synthetic esters, such as Midel 7131, Transol Synth 100, and Envirotemp 200, offer lower viscosity, higher fire points, and superior long-term oxidative stability than natural esters—making them particularly attractive for high-demand transformer applications (Oparanti et al., 2023; Rozga et al., 2020). However, synthetic esters also present several limitations, including higher production costs due to more expensive polyol alcohols (typically derived from petrochemical sources) and the need for complex esterification and purification steps to ensure high product purity. In addition, their relatively small production scale and stringent quality standards for transformer applications further increase costs (Lyutikova et al., 2022).

Most ester oil research is still limited to evaluating certain parameters without considering other factors that could comprehensively affect the long-term performance of insulating oils. How variations in fatty acid profiles affect the efficiency of insulating oils is a crucial aspect that remains underexplored. For instance, Suzuki et al. (2011) investigated how the molecular structure of

FAMEs, such as carbon chain length (C8 and C12), influences their dielectric performance by linking it to the molecular interaction mechanism with moisture. Kano et al. (2012) reported that ester oils synthesized from saturated fatty acids (SFA) of palm oil could sustain breakdown voltages near 80 kV despite water concentrations ranging from 15 to 50–100 ppm. Simultaneously, moisture inside natural ester oil surged from 43 to 500 ppm, attributed to its unsaturated fatty acid (UFA) profile, which decreased its breakdown voltage from 77 to 60 kV. Spohner etal. (2013) demonstrated that the relative permittivity of ester oil containing methyl oleate significantly declines from 3.11 to 2.49 when subjected to temperature variations, whereas methyl stearate (C18:0) exhibits a smaller reduction from 2.67 to 2.38. These findings indicate that ester-based insulating fluids, particularly those rich in molecular chains containing multiple double bonds, have a higher tendency toward thermal instability. Similarly, Shill et al. (2022) explored the impact of different saturated-to-unsaturated fatty acid ratios on lightning impulse breakdown voltage (LIBDV). The findings have demonstrated that oils containing more saturated acids have higher LIBDV. Nevertheless, existing studies have primarily focused on evaluating how variations in FA profiles influence the preliminary characterization of ester oils, often considering only a limited set of parameters.

Although ester oil offers various advantages, its implementation remains challenging mainly because of higher costs and large investments in transformer unit replacement (Rozhentcova et al., 2020). The retrofilling method—defined as the process of replacing aged mineral oil (AMO) in an existing transformer with a new insulating liquid, typically ester oil, without replacing the transformer unit—has emerged as a more cost-effective alternative to overcome these obstacles. The standard retrofilling process generally involves draining the old oil, flushing with hot ester oil (minimum 60°C) to dissolve residual AMO, replacing all gaskets and seals with compatible materials, degassing, and refilling with new ester oil under vacuum. However, residual AMO remains a major technical concern. Up to 10% of the previous oil may be trapped in the porous insulation, core windings, and internal surfaces, which can significantly influence the dielectric, thermal, and chemical properties of the new ester oil in both the short and long term (Beroual et al., 2018). To date, there is no universal standard regulating the maximum allowable mineral oil residue or the precise FA composition for each ester oil. Nevertheless, several studies recommend keeping the residual mineral oil content below 10% to ensure optimal performance and maintain the fire safety classification of ester-based fluids. In Indonesia, retrofilling has generally been practiced as the replacement of AMO with fresh mineral oil, especially in the transformer maintenance activities of PLNs. However, retrofilling with ester-based insulating oils has not yet been widely implemented and remains in the research and pilot study stages.

The blend of different oils enhances the heat tolerance and electrostatic insulation properties of bio-based ILs. Wei et al. (2020) reported that the fire resistance of ester oil declines when the residual mineral oil concentration exceeds 7%, causing its fire point to fall below 300°C, thereby disqualifying it from the K-class classification as a flame-resistant insulating fluid. However, Othman et al. (2023) found that a blend of 7% Nytro Libra and 93% Midel 7131 had a lower acid number than a blend with 3% mineral oil residue. In contrast, Song et al. (2024) showed that the lower the mineral oil residue, the higher the dielectric dissipation factor, thereby increasing the heat energy loss. These differences emphasize the importance of comprehensive technical evaluation in retrofilling ester oils, especially in maintaining thermal stability, dielectric compatibility, and long-term degradation resistance.

Therefore, this study aims to comprehensively evaluate the impact of AMO residue and FA composition on the dielectric and physicochemical performance of natural (NEO) and synthetic (SEO) ester oils under accelerated thermal aging to fill these crucial knowledge gaps. This work contributes by providing head-to-head technical data that advances previous research, which has typically considered these factors in isolation, and provides a technical assessment relevant to Indonesia's future retrofilling policy. The main novelty of this research lies in its in-depth analysis that links macroscopic performance degradation with the underlying transformations in the FA composition profiles. Specifically, this novelty is achieved by intentionally investigating the influence of AMO residue proportions in the critical range of 7.5%–9.5%—a zone where safety properties are known to begin degrading—thereby filling a significant data gap that has not been systematically mapped in previous studies.

2. Methods

2.1. Materials

Two commercial ester-based transformer oils, along with one sample of AMO, were obtained and used as received. The SEO selected was Midel 7131, generously provided by Midel & Mivolt Fluids Ltd. Biotran-35, a commercial product from Dongnam Petroleum Ind. Co. Ltd., was used as the NEO. AMO was sourced from a 150 kV GIS transformer in the PT PLN (Persero) UITJBB working area that had been in service for less than 10 years. Table 1 presents the manufacturers' specifications for both new ester oils.

Table 1 Product data sheet specifications for NEO and SEO

No.	Criteria	Unit	Midel 7131	Biotran-35
1	BDV	kV	94.4	74.6
2	Water Content	mg/kg	43	46.5
3	Color	-		0.5
4	Density [20°C]	g/cm³	0.97	0.92
5	Acid Numbers	mg KOH/g	0.024	0.038
6	Viscosity [40°C]	mm²/s	29.2	34.62
7	Flash Point	˚C	263	258
8	Fire Point	˚C	318	354

2.2. Experimental Setup

This study evaluates the role of AMO residue and FA distribution in shaping the dielectric characteristics of ester-insulating fluids applied in transformer retrofilling at PT PLN (Persero), as illustrated in Figure 1.

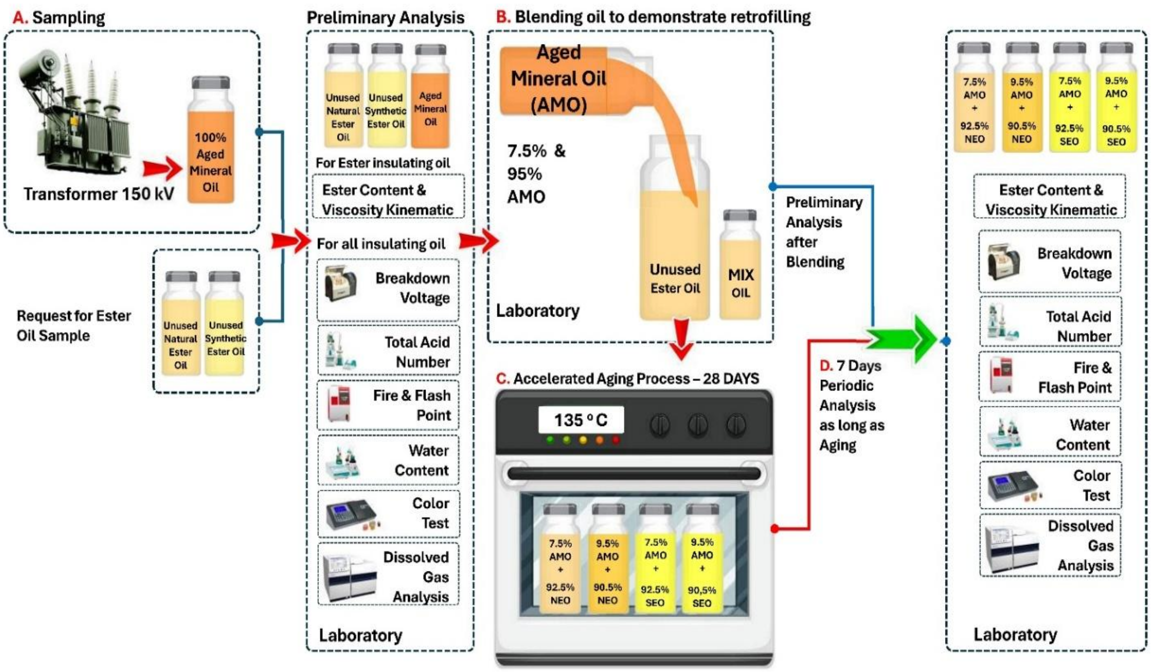


Figure 1 Schematic of the experimental workflow. The process involved four main stages: (a) sampling and preliminary characterization of the base oils (SEO, NEO, and AMO); (b) blending of

ester oils with AMO at 7.5% and 9.5% concentrations to simulate retrofilling; (c) accelerated thermal aging of the mixtures at 135°C for 28 days; and (d) periodic analysis of key dielectric and physicochemical properties at 7-day intervals. (SEO: synthetic ester oil; NEO: natural ester oil; AMO: aged mineral oil).

2.2.1. Preparation of the oil samples

In this study, SEO and NEO were mixed with AMO at concentrations of 7.5% and 9.5%, respectively, to represent the residual oil in the transformer. These fractions were based on the findings of Scatiggio et al. (2023), who found that mineral oil residues in transformer insulation systems reach 10%. In addition, this ratio was chosen to fill the gap in previous studies (Song et al., 2024; Othman et al., 2023; Qian et al., 2023), which did not explore the influence of mineral oil residue on the ratio. Ning et al. (2024) evaluated ratios of 7.5% and 10% but did not cover 9.5%.

Over 24 hours, the Duran glass bottles (1000 mL) were maintained at 110°C for 24 h after thorough cleaning and drying to eliminate residual moisture and contaminants. AMO samples with SEO or NEO were placed in glass bottles and homogenized for 2 h using a stirrer for 2 h. The homogenized mixture was then divided into five glass bottles labeled according to the aging periods of 0, 7, 14, 21, and 28 days. This procedure was designed to ensure sample homogeneity and to prevent contamination during collection at each test stage.

2.2.2. Accelerated thermal aging

Experiments on power transformers under operational conditions are time-consuming and costly (Ortiz et al., 2018). Therefore, a controlled laboratory-scale experiment was designed to accelerate the degradation simulation in a blend of ester- and mineral-based oils. The accelerated aging approach allows for a more efficient evaluation of oil performance within a manageable timeframe. This process is intended to replicate the long-term aging and degradation experienced by insulating oils over years of real transformer operation in weeks.

The underlying principle is that increased operating temperature accelerates chemical degradation exponentially. According to Montsinger's rule, the service life of insulation is halved for every 8°C increase in operating temperature. This relationship is expressed in Equation (1):

$$Factor\ aging\ accelerating\ (FAA_{8\,°C}) = \frac{T_{aging\ (°C)} - T_{ref\ (°C)}}{8\ °C} \tag{1}$$

where $FAA_{8°C}$ is the aging acceleration factor based on 8°C increments, T_{aging} is the aging temperature in °C, and T_{ref} is the reference temperature in °C.

Then, the total acceleration factor was calculated using the doubling rule (Equation 2):

$$Factor\ Time\ (FT) = 2^{FAA_{8°C}} \tag{2}$$

where FT denotes the total acceleration time factor

Following the guidelines outlined in IEC 60216-1:2013 and IEEE Std C57.100™-2011, accelerated aging was conducted at a test temperature of 135°C for 28 days. Based on IEEE C57.91-2011, a temperature of 135°C results in an accelerated aging of 11.02 times compared with a reference temperature of 110°C. However, this study uses a different approach. The reference temperature (T_{ref}) of 65°C was specifically chosen to represent the actual operational temperature range (60°C–70°C) of power transformers operated by PT PLN (Persero) UITJBB in Indonesia (Karaman et al., 2023; Emara et al., 2017; Wada et al., 2013), ensuring that the accelerated aging protocol is relevant to local field conditions. Using Equations (1) and (2), the calculated FT is approximately 430.54, indicating that the laboratory experiment simulates a much longer operational period in real service. The equivalent service life simulated by the laboratory test is calculated according to Equation (3):

$$Transformer\ aging\ time\ equivalence\ (TaTe) = \frac{Number\ of\ laboratory\ aging\ days}{365\ days} x\ FT \tag{3}$$

where TaTe is the equivalent service life in years, FT is the factor time, and 365 days is the number of days in a year.

Therefore, testing at 135°C for 28 days is equivalent to approximately 33 years of transformer operation at 65°C. This protocol aligns with previous studies conducted at 150°C or within a temperature range of 90°C–130°C (Karaman et al., 2023; Alshehawy et al., 2019; Mohamad et al., 2018; Emara et al., 2017), but is specifically adapted to reflect actual field conditions in Indonesia. No metal catalyst was added during the thermal aging process (Das, 2023).

2.2.3. Measurement, collection, and data processing

The pure insulating oils (SEO, NEO, and AMO) were subjected to preliminary tests before aging. The samples were examined in five aging periods at 7-day intervals (Table 2) to evaluate the impact of aging, as done by Gengadevi and Madavan (2023). Furthermore, a quantitative analysis was performed to identify the FA composition of SEO, NEO, and their mixtures, with periodic evaluations conducted at 0, 14, and 28 days. This study aimed to determine how different compositions affect the electrical insulation properties of oil blends when used in transformer applications.

The quantitative assessment used instruments compliant with the IEC, ASTM, and ISO standards (Table 3). Oil testing was conducted in three accredited laboratories: the PT PLN (Persero) UITJBB Transformer Oil Laboratory, the University of Indonesia Department of Chemical Engineering Laboratory, and the PT Hyprowira Adhitama Laboratory.

Table 2 Sample conditions and the aging process

No.	Sample Code	Esters (%)	Mineral oil content (%)	Temperature (°C)	Duration (days)	Periodic sampling (days)
1	92.5SEO:7.5AMO	92.5	7.5	135	28	0; 7; 14; 21; 28
2	90.5SEO:9.5AMO	90.5	9.5	135	28	0; 7; 14; 21; 28
3	92.5NEO:7.5AMO	92.5	7.5	135	28	0; 7; 14; 21; 28
4	90.5NEO:9.5AMO	90.5	9.5	135	28	0; 7; 14; 21; 28
5	SEO	100	0	30	0	0
6	NEO	100	0	30	0	0
7	AMO	0	100	30	0	0

Table 3 Test standards and equipment used

Oil Characteristic	Testing Standards	Instrument
Breakdown Voltage	IEC 60156	Megger OTS100AF
Water Content	IEC 60814	Metrohm 917 Coulometer (KF)
Acid Numbers	ASTM D664	Metrohm 848 Titrino Plus
Color	ASTM D1500	Lovibond PFXI 195-2
Flash Point	ISO 2719	Eraflash Type EF 10
Fire Spots	ISO 2719	Pensky-Martens Closed Cup
Kinematic Viscosity [40°C]	ASTM D445	Tamson Instrument, AK Viscometer
Fatty acid composition	DIN EN 14103	GC-FID PerkinElmer

3. Results and Discussion

This section details the results of the accelerated aging experiments and discusses their scientific implications. Table 4 provides an initial comparative context and summarizes the key findings alongside relevant literature.

Table 4 Summary of key findings on ester oil-mineral oil blends

Parameters	This Study	Das et al. (2023)	Gengadevi and Madavan (2023)	Othman et al. (2023) and Wei et al. (2020)
Breakdown voltage (BDV)	An increase in SEO but a decrease in NEO upon initial contamination, highlighting the role of ester structure.	Mineral oil contamination generally lowers BDV but notes an actantial increase for saturated esters (coconut oil).	A strong correlation was found between aging and BDV degradation in natural esters, which aligns with our findings for NEO.	Not Reported
Total acid number (TAN)	Massive increase in oxidation-driven SEO and moderate increase in hydrolysis-driven NEO.	Not Reported		Othman et al. reported a complex, non-linear TAN behavior in mixtures, which is consistent with our NEO findings.
Viscosity	Remarkably stable during aging, suggesting chain scission as the dominant mechanism over polymerization.	Not Reported	A continuous rise in viscosity was observed, indicating that polymerization was the dominant mechanism in their system.	Not Reported
Fire Point	K-class status is lost upon contamination. NEO showed superior stability during aging compared with SEO.	Not Reported	Not Reported	Wei et al. also reported the loss of K-class status when AMO contamination exceeded 7%.
The primary focus of the study	To link macroscopic degradation with fatty acid profile transformation under specific contamination and aging scenarios.	To compare the AC breakdown strengths of different natural esters (coconut vs. soybean).	To analyze the aging performance of various non-edible natural esters and their insulation systems.	To classify fire safety (Wei) and correlate TAN with Fourier-transform infrared spectroscopy (Othman).

3.1. Impact of AMO Residue and Aging on Ester Oil Performance

3.1.1. Dielectric Strength

The breakdown voltage (BDV), a critical indicator of dielectric performance, was found to be influenced by the AMO residue concentration. As illustrated in Figure 2a, samples with 9.5% AMO contamination consistently exhibited a higher and more stable BDV compared to those with 7.5% AMO for both ester oil types.

During the initial blending, the BDV of SEO increased from 75.3 kV/2.5 mm (Table 5) to 85.6 and 88.4 kV/2.5 mm with 7.5% and 9.5% AMO, respectively. In contrast, under the same conditions, NEO experienced a BDV decrease of 8.09% and 18.79%. This pattern diverges from the general trend reported by Das (2023), who found that the addition of AMO to ester-based insulating oils typically resulted in a decrease in BDV. However, Das (2023) also observed that a small proportion of mineral oil (up to 10%) could actually enhance BDV in certain cases, such as for coconut oil—a saturated natural ester. This suggests that the response of BDV to AMO contamination may depend on the ester oil's underlying FA composition, particularly its degree of saturation.

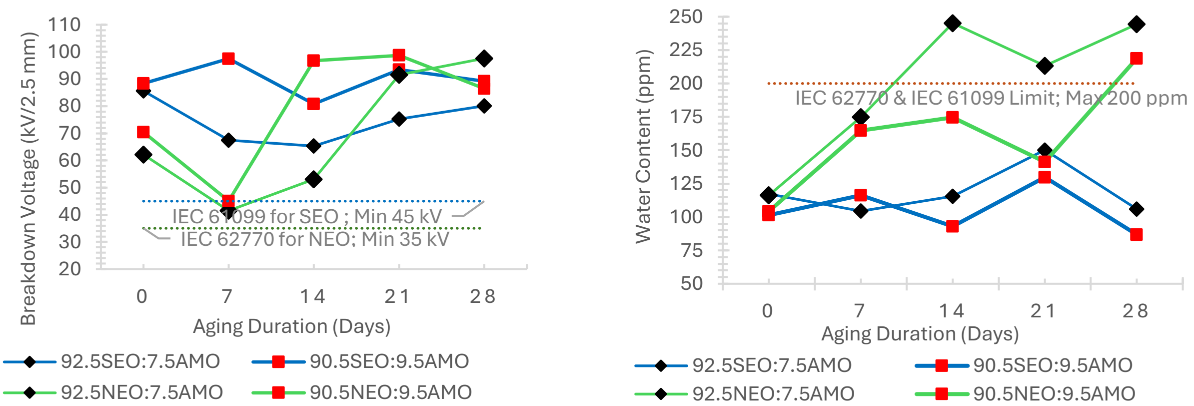
Compared with the mixture of plant-derived ester oil (Midel eN1215) and petroleum-based oil in Das's study, the BDV results in this work were generally higher, which may be attributed to the distinct FA profiles and oxidative stability of the tested esters. Thus, the observed modifications in the dielectric attributes of ester-based insulating oils can be linked to differences in fatty acid content and distribution, a conclusion also supported by Das et al. (2023), who noted the superior dielectric performance of saturated synthetic esters and their resistance to moisture effects.

On the 7th day of aging, a sharp decrease in BDV was observed in all samples except for 90.5SEO:9.5AMO. Subsequently, BDV values gradually increased and remained above 80 kV/2.5 mm until the end of the aging period. This trend likely reflects the complex interplay between early degradation of AMO components and secondary chemical reactions during aging, as also noted by Dewi et al. (2018), who found an initial drop followed by a recovery in BDV over prolonged aging. Furthermore, SEO exhibited higher BDV stability than NEO across all AMO concentrations, a result consistent with the findings of Khan et al. (2021). Spearman's correlation analysis of SEOs showed a weak relationship between BDV and aging ($\rho \leq -0.10$), confirming that aging time does not strongly influence BDV changes. Conversely, for NEO, BDV showed a moderate to strong correlation with aging ($\rho \geq 0.6$), which is in agreement with the work of Gengadevi and Madavan (2023).

The relationship between moisture content and BDV was generally weak ($\rho \leq 0.10$), consistent with the findings of Das (2023), Das et al. (2023), and Khan et al. (2021) but in contrast to Beroual et al. (2018), who reported a more pronounced impact in mineral oil-based systems. Overall, the BDV values of all samples remained above the IEC 62770 and IEC 61099 minimum standards throughout the aging period, with the average BDV for SEO at 82.31 kV/2.5 mm and 74.33 kV/2.5 mm for NEO. These results underscore the robustness of ester-based oils, particularly those rich in saturated fatty acids, in maintaining dielectric strength under both AMO contamination and accelerated aging scenarios who reported a more pronounced impact in mineral oil-based systems. Overall, the BDV values of all samples remained above the IEC 62770 and IEC 61099 minimum standards throughout the aging period, with the average BDV for SEO at 82.31 kV/2.5 mm and for NEO at 74.33 kV/2.5 mm. These results underscore the robustness of ester-based oils, particularly those rich in SFAs, in maintaining dielectric strength under both AMO contamination and accelerated aging scenarios.

Table 5 Preliminary test results for the mineral and ester oils

Parameters	Unit	Aged mineral oil	Midel 7131	Biotran-35
Breakdown Voltage	kV/2.5 mm	41.3	75.3	76.6
Water Content	ppm	41.9	110.23	87.3
Total acid number	mgKOH/g	0.0330	0.0217	0.0354
Color	-	2.1	0.1	0.8
Flash Point	°C	146.33	256.3	226.97
Fire Point	°C	-	316.4	306.4
Kinematic viscosity (40°C)	cSt	-	37.618	33.005



(a) (b)

Figure 2 Changes in (a) BDV and (b) water content as a function of aging duration for all tested ester-AMO mixtures

3.1.2. Moisture levels

The presence of moisture in the insulating oil is a decisive element in shaping its dielectric performance, exerting a significant effect on its chemical and physical attributes during transformer operation. Excessive moisture can trigger bubble formation or create conductive pathways, which may compromise the dielectric structure if the saturation threshold and standard limits are exceeded. Ester oil has a strong affinity for absorbing water, including moisture trapped in insulating paper, thereby enhancing transformer longevity (Dumitran et al., 2019). This strong affinity is primarily due to the ester bonds' polar nature, which can interact with polar water molecules through dipole interactions and hydrogen bonding. The test results (Table 5) indicate that newly synthesized ester oil exhibits significantly higher moisture retention—approximately two to three times greater—than petroleum-based insulating oil that has been operational for less than a decade. While petroleum-based insulating fluids are more susceptible to dielectric breakdown due to moisture, ester-based oils retain stable BDV, even with higher water absorption (Villarroel et al., 2021; Martin et al., 2013).

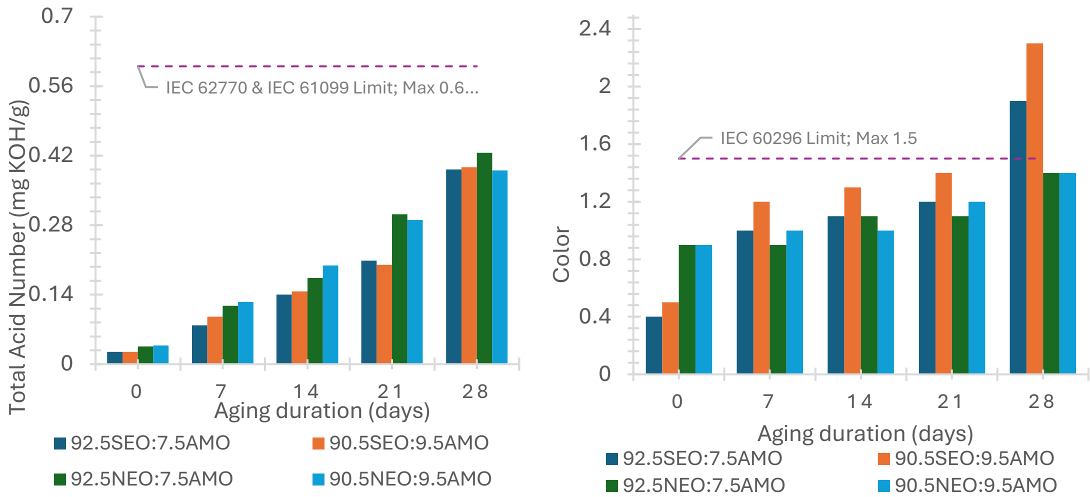
Figure 2b illustrates that the moisture levels in SEO remained moderate within the IEC 62770 and IEC 61099 limits (≤ 200 ppm). However, this parameter is often quantified as water content in technical analysis and standard measurement methods. In this context, NEO exhibited a significant increase in water content during aging, particularly on day 7, with spikes of 245.2 ppm (92.5 NEO:7.5 AMO on day 14) and 218.8 ppm (90.5 NEO:9.5 AMO at the end of aging), exceeding standard thresholds. This finding differs from that of Jayyid et al. (2024), who reported that SEO exhibited higher moisture content than NEO during aging at 100°C and 125°C. This apparent discrepancy likely highlights the critical influence of experimental conditions; our study's higher aging temperature (135°C) and the presence of AMO contaminants may have significantly accelerated the specific water-producing degradation pathways (hydrolysis and oxidation) in NEO, an effect potentially less dominant at the lower thermal stresses investigated by Jayyid et al. (2024). However, our observation that NEO tend to absorb more water as the aging period progresses is consistent with the findings of Gengadevi and Madavan (2023) and Rouabeh et al. (2019).

In addition, the transformer insulating oil's oxidative decomposition produces additional water (Qin et al., 2024). For NEO, this creates a "vicious cycle" effect, where initially absorbed moisture accelerates hydrolysis and oxidation, which in turn generates more water as a by-product, further promoting degradation. Consequently, natural ester oil retains more moisture than synthetic ester oil. Consequently, NEO exhibits a higher tendency to retain moisture than SEO, as confirmed by Yoon and Chen (2021). However, it is noteworthy that all tested samples remained within the permissible threshold (<350 ppm) as specified by IEEE C57.147-2018 guidelines for transformer retrofilling (IEEE, 2018).

3.1.3. Total acid number (TAN)

Aging due to thermal oxidation is a major factor that accelerates the degradation of ester-based insulating oils. Throughout the oxidation and hydrolysis process, various oxygenated compounds—such as carbonyl-containing substances, including aldehydes and ketones, and alcohols and carboxyl acids—are generated. Consequently, the neutralization number experiences an upward shift (Zhang et al., 2024). TAN reflects the degree of oil degradation due to thermal oxidation, where the data in Table 5 show values of 0.0217 and 0.0354 mgKOH/g for SEO and 0.0354 mgKOH/g for NEO, which are relatively close to 0.0333 mgKOH/g in AMO. The carbonyl group content in ester oils increases the initial TAN content compared to AMO (Rozga et al., 2020)

At 135°C, TAN values increased linearly with aging time with a correlation of $R^2 > 0.9$. The 92.5SEO:7.5AMO sample had a stronger correlation ($R^2 = 0.9209$) than 90.5SEO:9.5AMO, while 90.5NEO:7.5AMO had a stronger correlation ($R^2 = 0.9974$) than 92.5NEO:7.5AMO. Figure 3a shows that NEO has a higher TAN than SEO, although the increase in the TAN of SEO is more significant, reaching 1729.8% at the end of aging. This remarkable rise in TAN for SEO indicates a strong impact of AMO and accelerated oxidation, which is consistent with the findings of Bandara et al. (2015), who observed that synthetic esters, such as Midel 7131, show more rapid TAN escalation than natural esters at elevated temperatures. This suggests that the structure and composition of SEO increase its susceptibility to acid formation during high-temperature aging, particularly when mixed with AMO.



(a) (b)

Figure 3 Evolution of (a) TAN and (b) color index during the 28-day accelerated aging process

Interestingly, the increase in TAN in SEO was not strongly correlated with water content ($R^2 < 0$), further supporting the thermal oxidation dominance over hydrolysis in this process. In contrast, the TAN of NEO showed a strong correlation with moisture content ($R^2 \geq 0.7$), indicating that hydrolysis and the formation of free fatty acids (FFA) are significant contributors to the increase in TAN in NEO during aging. This result is consistent with that of Othman et al. (2023), who reported that blends with a lower proportion of mineral oil tend to have higher TAN values, likely due to more active acid-generating reactions in ester-rich systems.

Consistent with Gengadevi and Madavan (2023), the results also show that mineral oils can experience a substantial TAN increase (up to 1020%) during prolonged aging, highlighting the need for continuous monitoring of acid number in both ester- and mineral-based insulating fluids. Overall, these findings underscore the importance of understanding the different mechanisms driving acid formation in various insulating oils and their blends, especially for long-term reliability and maintenance planning.

3.1.4. Color

Assessing the color of transformer fluids serves as an initial diagnostic tool for detecting degradation, contamination, oxidation, and thermal aging effects. Oxidative reactions produce carbonyl compounds, peroxides, and dispersed carbon particles that increase the color index and cause a darker color change (Sibuea and Suwarno, 2022). Figure 3b shows an increase in the color index during aging, with NEO exhibiting better color stability than SEO. Thermal oxidation increased the color index of the SEO from 0.4 to 0.5 and from 1.9 to 2.3. In contrast, NEO increased from 0.9 to 1.4, which is lower than the values reported by Duanaputri et al. (2024) for NEO aged at 150°C for 720 h (color index reaching 3-3.5). This difference is likely attributable to the higher aging temperature and longer duration used in their study, which accelerates oxidation and color change.

In addition to oxidation, mineral oil residues with a color index of up to 2.1 contributed to the oil blend's color increase. Note that mineral oil typically tends to darken more quickly under oxidation than esters; therefore, its presence in the blend can enhance the darkening process. Slow discoloration indicates increased resistance to oxidation and contamination, which extends the life of the oil and minimizes the need for maintenance (Hadi et al., 2021). The IEC 62770 standard does not specify a color index limit; however, considering IEC 60296, which has a maximum of 1.5, all SEO samples exceeded the threshold at the end of the aging process. Exceeding the color index threshold is primarily a visual concern and does not directly indicate electrical failure. However, it serves as a warning for increased oil aging and actantial future issues. The oil's oxidative resistance is predominantly controlled by its inherent chemical structure and the oil fraction used in the blend.

3.1.5. Flashpoints and fire points

The ability of an insulating oil to withstand ignition, as measured by its flash and fire points, significantly enhances transformer fire safety. A high parameter value leads to a lower risk of transformer explosion (Yu et al., 2017). Therefore, a decrease in these probability values when ester oil is applied during transformer retrofilling is important. Table 5 shows that the SEO and NEO samples have higher flash points than the AMO sample. In addition, SEO and NEO have a fire point higher than 300°C; therefore, according to IEEE C57.147-2018 (IEEE, 2018), they are referred to as K-class flame-retardant grade oils.

However, after AMO contamination, the class K category changed to class O because the flash point of the mixture decreased significantly below the 300°C limit. Blends including 92.5SEO:7.5AMO, 90.5SEO:9.5AMO, 92.5NEO:7.5AMO, and 90.5NEO:9.5AMO displayed a reduction in the flash point at the onset of blending to 238.3°C, 222.3°C, 250.4°C, and 246.3°C, respectively. This pronounced decrease can be attributed to the presence of low-molecular-weight hydrocarbon fractions in AMO, which are more volatile and lower the blend's overall thermal stability. Such effects have also been reported by Qian et al. (2023) and Wei et al. (2020), who observed that increasing AMO fractions in ester-based blends causes a notable drop in both flash and fire points, thereby reducing fire safety.

Under the initial conditions, the flash point of SEO reached 316.4°C, which is approximately 10°C higher than that of NEO and Midel 7131 tested by Dombek and Gielniak (2018). Although this difference is relatively modest, it highlights the slightly higher thermal stability of the SEO method. After blending and aging, NEO exhibited better retention of its fire point compared with SEO, suggesting greater stability under prolonged stress. The average flash point of NEO reached 240.35°C, with a range of 51.83°C across AMO ratios, whereas that of SEO averaged 230.37°C, with a smaller difference of 17.43°C. These data indicate that NEO may be more resilient against fire point reduction over a broader range of contamination, which is beneficial for applications requiring sustained fire resistance.

Overall, the fire and flash points of the SEO and NEO blend samples were relatively stable during aging. Due to experimental error, the 90.5NEO:9.5AMO sample experienced a sharp drop in the flash point to 214.3°C on the 14th day of aging. Importantly, according to IEEE and IEC standards, maintaining a flash point above 300°C is essential for K-class applications; if the value falls below this threshold, the oil may no longer meet the fire-retardant requirements and thus poses a higher fire risk in transformer operation.

3.1.6. Viscosity

The ability of a transformer to dissipate heat is significantly affected by the properties of its insulating oil, particularly its viscosity. A high viscosity can inhibit fluid flow, slow heat dissipation, and increase the operating temperature. The results showed that the viscosity of SEO and NEO at all AMO volume fractions was fairly stable during aging, although there was a slight decrease on day 14 for the 9.5% AMO volume fraction. This finding differs from that of Gengadevi and Madavan (2023), who identified a continuous rise in the viscosity of ester-derived insulating liquids over time, ultimately degrading the heat dissipation efficiency of the system. This suggests that viscosity stability is not solely dependent on the duration of thermal oxidation but is also influenced by the ester-based and petroleum-derived oil interaction in the mixture.

This is in contrast to the findings of Ning et al. (2024), who observed a consistent reduction in the viscosity of ester oil with increasing AMO fraction. Our results showed that for SEO and NEO, viscosity increased at 9.5% AMO compared to 7.5% AMO (Figure 4), possibly reflecting unique characteristics of the residual mineral oil used or differences in the initial viscosity and aging conditions compared to Ning et al. (2024). In addition, the viscosity of the synthetic ester blend tested at a mineral oil ratio of 7.5% decreased by 3.01–26.03 cSt. Such variations highlight the complex interactions between ester and mineral oil components, which can either increase or decrease viscosity depending on the chain length and hydrocarbon fractions' volatility.

The elevated viscosity of ester-based insulating oils restricts their cooling performance, necessitating greater cooling efforts and raising operational costs, particularly in transformer retrofilling (Kiran et al., 2022). Nonetheless, the observed drops in viscosity during aging, as also noted by Karaman et al. (2023) and Scatiggio et al. (2019), suggest that temperature-induced breakdown of longer ester chains and the dilution effect from AMO may partially offset viscosity concerns, especially at typical transformer operating temperatures (below 15 cSt at 50°C and 10 cSt at 75°C). In addition, ester oils possess greater thermal conductivity than mineral oils (Goscinski et al., 2023), potentially compensating for higher viscosity in real-world heat management.

The average kinematic viscosities of the SEO and NEO blend samples reached 27.845 and 34.021 cSt, respectively, exceeding the maximum limit of 25 cSt according to SPLN 49-1-1982 applicable to mineral oils (Bukit et al., 2021). However, because this national standard does not yet cover ester oils, the assessment should refer to international standards such as IEC 62770:2013 and IEEE C57.147-2018, both of which set a maximum viscosity limit of 50 cSt. Therefore, the viscosity values reported here remain within the globally accepted limits for transformer retrofilling. Thus, the ester oil retrofilling method is feasible.

Further analysis was conducted to examine the correlation between TAN and viscosity across all aging periods and AMO fractions. Statistical evaluation showed no significant correlation between these two parameters (Pearson's $r = 0.016$, $p = 0.945$; Spearman's $\rho = -0.106$, $p = 0.656$). This finding confirms that the processes responsible for acid formation, mainly oxidation and hydrolysis, occur independently of those influencing viscosity, such as chain scission or dilution by mineral oil. Consequently, an increase in TAN does not necessarily translate into a rise in viscosity for ester-based insulating oils, which is in line with the reports by Gengadevi and Madavan (2023) and Scatiggio et al. (2019).

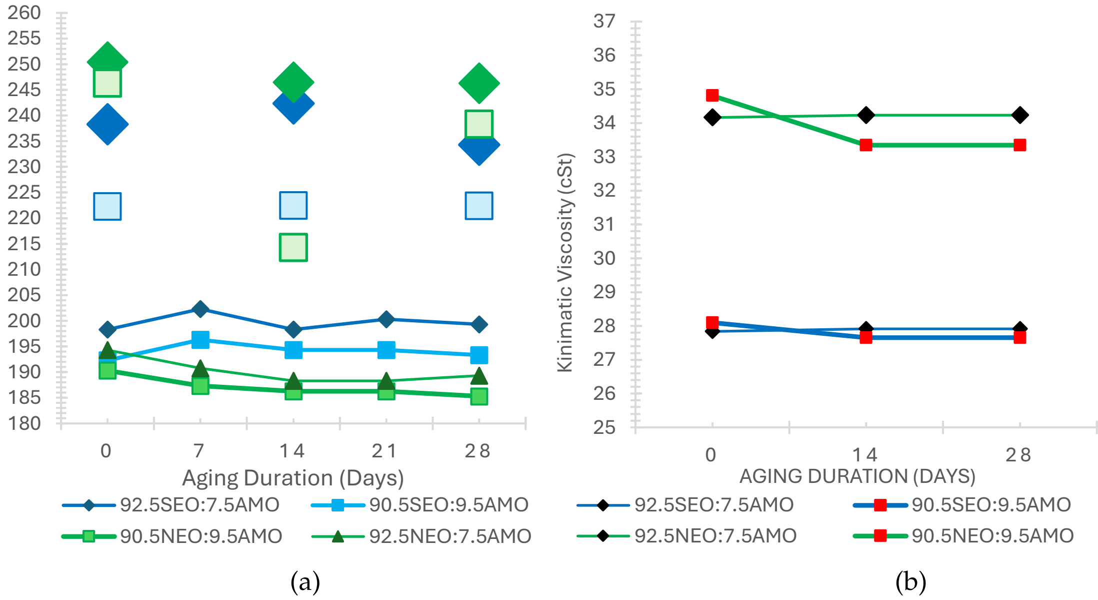


Figure 4 Changes in (a) flash and fire points and (b) kinematic viscosity as a function of aging duration for all tested ester-AMO mixtures

3.2. Effect of fatty acid composition on ester oil performance

3.2.1. Natural Ester Oil (NEO)

The quantitative analysis of fatty acids showed that C18:0 saturated fatty acids (41.79%) and C18:1 UFA (35.43%) dominated NEO. The total SFA content reached 64.57%, indicating high stability against oxidation (Sharma et al., 2020). Figures 2a and 6 show the influence of the proportion of monounsaturated fatty acids on the dielectric characteristics of ester-based insulating oils. The BDV of the 90.5NEO:9.5AMO sample with a C18:1 content of 38.35% was 70.4 kV/2.5 mm, whereas that of the 92.5NEO:7.5AMO sample with a higher C18:1 content (40.50%) was 62.2 kV/2.5 mm. This comparison shows a negative relationship between UFA content and BDV, where a decrease in C18:1 content correlates with an increase in BDV.

As the fraction of unsaturated fatty acids in NEO-AMO mixtures increased, a corresponding decline in kinematic viscosity was observed. The 90.5NEO:9.5AMO formulation exhibited a viscosity of 34.808 cSt, whereas a slightly lower value of 34.163 cSt was recorded for the 92.5NEO:7.5AMO blend. This pattern is consistent with the findings of Bukit et al. (2021), who demonstrated that the incorporation of ester-based oil into petroleum-derived insulating oil consistently resulted in reduced viscosity within the blend.

The saturated fatty acid content remained relatively stable during aging. However, a significant decrease in C22:0 and C24:0 was observed after blending with AMO. The reduction rate reached 94.22-95.85%. Interestingly, the TAN value did not significantly increase (0.0354 mgKOH/g to 0.0355-0.0378 mgKOH/g). Therefore, hydrolysis can be ruled out as the main cause of the aforementioned. Because saturated fatty acids are more inert to oxidation, oxidative degradation is not a dominant factor. Although the literature states that ester oils are fully soluble in mineral oils (Malde et al., 2023), this study shows a difference. The incompatibility of fatty acids with different chain lengths in mineral oils may contribute to phase separation. Zheng et al. (2021) proved that triglycerides with long carbon chains have lower solubility in hydrocarbon-based oils. Instead of undergoing chemical degradation, C22:0 and C24:0 may segregate or precipitate as microcrystals.

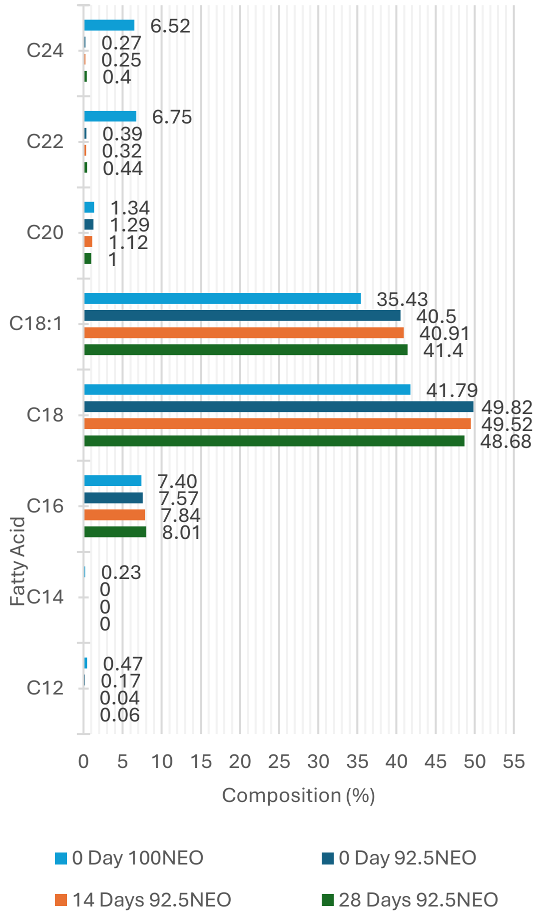
The increase in saturated and unsaturated fatty acid levels during aging is another interesting phenomenon. A considerable increase in the total acid content was observed in conjunction with this process (Figure 3a). The increase in TAN is closely associated with the emergence of FFA, which originate from hydrolysis and oxidation reactions. However, no decrease in C18:1 was observed in this study, which should be more susceptible to oxidation than saturated fatty acids. These results pose a challenge in understanding the stability of natural ester oils during oxidation. Amores and Virto (2019) reported that the GC-FID method cannot distinguish between FAME and FFA. Therefore, the detected increased levels of C18:1 and C18:0 may be due to the partial hydrolysis of FAME. It is possible that FFA was converted to FAME (Suriaini et al., 2021) during the preparation of the test sample.

3.2.2. Synthetic Ester Oil (SEO)

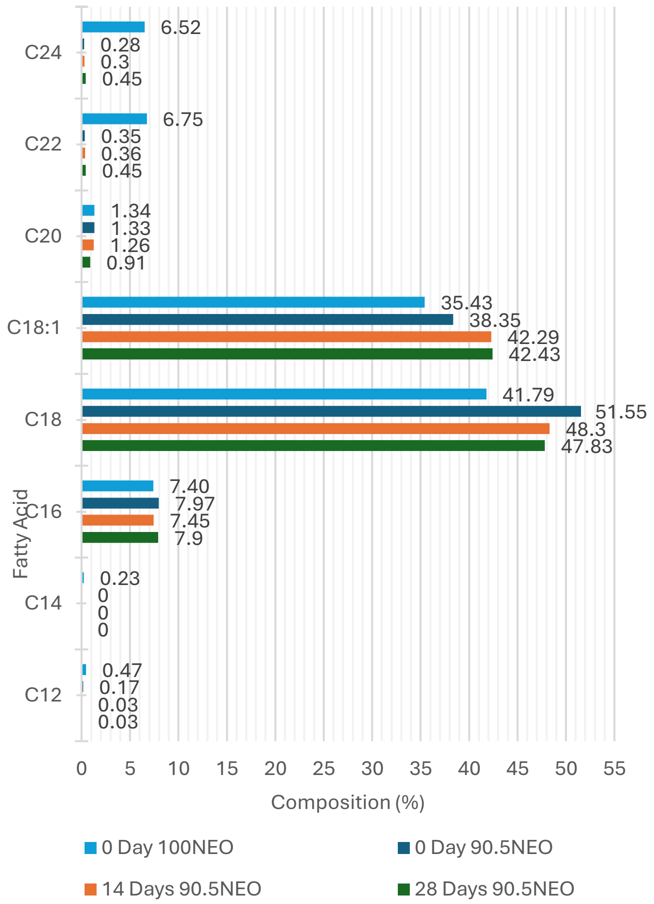
In contrast to NEO, SEO has a more restrained molecular structure because it is obtained through esterification or transesterification of vegetable oils with alcohols and catalysts to obtain more stable thermal and dielectric properties than mineral oil (Maulida et al., 2020; Ravulapalli et al., 2019). Figure 6 provides an overview of the fatty acid esters of SEO, which span carbon chains from C10 to C24, a distribution closely matching NEO (C12-C24). Before contamination with AMO residues, SEO comprised 93.27% saturated fatty acid esters, which was much higher than that of NEO, with C18 (24.67%) and C22 (21.80%) as the main components, theoretically providing higher oxidative resistance. However, almost all saturated fatty acid esters in SEO were degraded, except C12, with C20-C24 decreasing to 0%, similar to NEO, while C18 in SEO decreased drastically to 94.19%, much greater than NEO. C18 in SEO (1.55% w/w) was not strong enough to maintain stability compared with NEO (33.89% w/w). The increase in the color index of SEO from 0.1 to 0.4 further corroborates the oxidative degradation of SFA esters.

The transformation of long-chain SFA into shorter-chain counterparts is suggested by the increased C12 concentration, which increased by 0.37 w/w across the volume fraction of mineral oil in SEO. This increase was accompanied by a reduction in viscosity across both samples, where the 92.5SEO:7.5AMO blend exhibited a decrease from 37.618 to 27.838 cSt, whereas that of the 90.5SEO:9.5AMO sample exhibited a decrease from 28.098 cSt. This trend aligns with the characteristics of lauric acid (C12), which possesses a relatively shorter hydrocarbon chain than other SFAs, leading to weaker intermolecular forces and improved fluidity within the mixture (Xue et al., 2021).

Consistent with this mechanistic perspective, Kamhoua et al. (2024) reported that PKOME, which features a monoester structure with high lauric acid (C12:0) content, exhibited markedly lower viscosity than both crude PKOME and mineral oil. However, their focus was primarily on structural class (monoester vs. triester) and thermal performance, without detailed analysis of how individual fatty acid profiles contribute to viscosity. In contrast, the present study explicitly correlates the increasing proportion of short-chain SFA—resulting from aging and mineral oil contamination—with viscosity reductions in SEO blends.



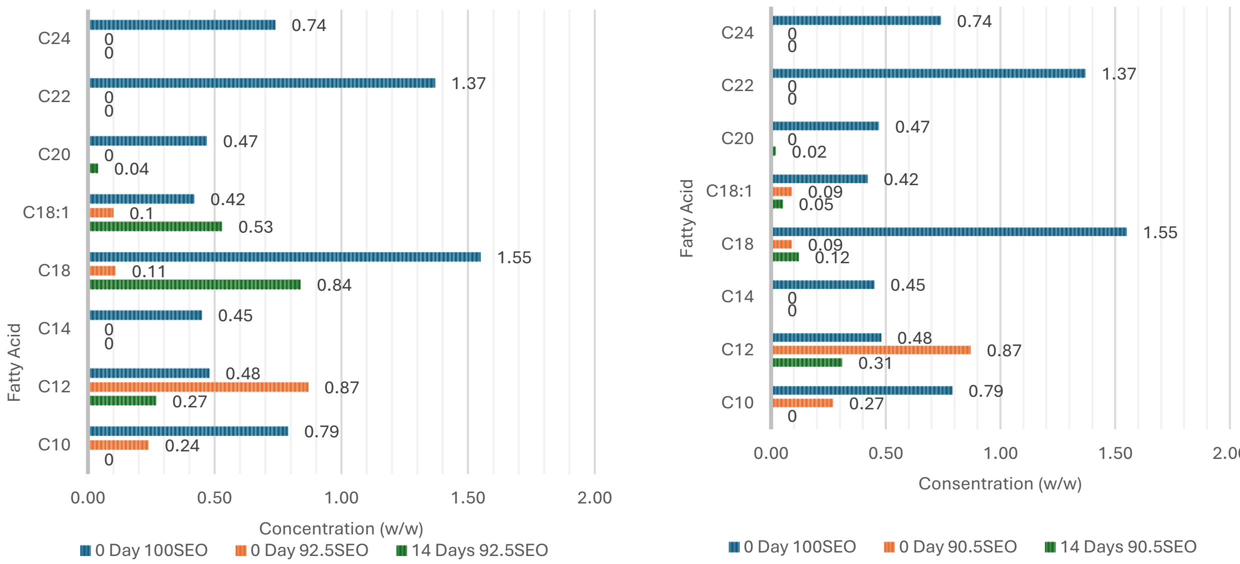
(a)



(b)

Figure 5 Impact of aging on FAs in (a) the 92.5NEO:7.5AMO and (b) 90.5NEO:9.5AMO groups

Furthermore, while Kamhoua et al. (2024) emphasized physical and thermal properties, our results extend the discussion by showing that dielectric BDV performance also reflects variations in fatty acid composition, such as C18:1 (oleic acid) levels. On day 14 of aging, the 92.5SEO:7.5AMO sample with a higher C18:1 content (0.53 w/w) exhibited a BDV of 65.3 kV/2.5 mm, whereas the 90.5SEO:9.5AMO sample with lower C18:1 (0.05 w/w) achieved a BDV of 80.8 kV/2.5 mm. This underlines the multifaceted influence of both chain length and unsaturation in fatty acid esters on transformer oil performance, highlighting aspects beyond those addressed in previous literature.



(a) (b)

Figure 6 Transformation of fatty acids during the aging process of (a) 92.5SEO:7.5AMO and (b) 90.5SEO:9.5AMO

4. Conclusions

This study confirms the technical viability of retrofilling transformers with both SEO and NEO, even in the presence of up to 9.5% AMO contamination. The primary contribution of this work is the elucidation that the optimal fatty acid composition for such applications is not absolute but is defined by a critical performance trade-off. As demonstrated by the superior BDV stability of the highly saturated SEO, a minimal content of UFA (e.g., C18:1) is paramount for maximum dielectric strength. For long-term chemical and thermal stability, a robust matrix of mid-to-long-chain saturated fatty acids proved more resilient to AMO-induced degradation, with NEO showing better fire point retention and SEO exhibiting better hydrolysis resistance. Concurrently, the controlled degradation into shorter chains (e.g., C12) was identified as a key mechanism for maintaining favorable low viscosity. These findings provide a more nuanced framework for selecting or designing next-generation insulating esters based on specific operational priorities. Three key avenues are recommended for future work to build upon these findings. First, investigating the synergistic effects of metal catalysts (e.g., copper) on these degradation pathways is critical to more accurately simulate the conditions inside an operational transformer. Second, a comprehensive techno-economic analysis is required to quantify each retrofilling option's long-term cost-efficiency benefits. Finally, expanding the research to include a wider variety of ester fluids and AMO compositions would help develop more robust and universal guidelines for the industry.

Acknowledgements

We thank PT PLN (Persero) for funding our research and publications and their assistance through the PBJJ Scholarship Program. We are also grateful to PT PLN (Persero) West Java Transmission Unit (UIT JBB) for granting us access to the necessary space and facilities for our research. Finally, we extend our gratitude to Mr. Budi Wicaksono of Midel & Mivolt Fluids Ltd. and Dongnam Petroleum Ind. Co. Ltd. for their generous donation of the research materials used in this work.

Author Contributions

David Silalahi: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing—Original Draft, and Visualization. Heri Hermansyah: Conceptualization, Supervision, Project Administration, Funding Acquisition, Resources, and Writing—Review & Editing. Patrick Cognet: Supervision, Validation, and Writing—Review & Editing. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors confirm that this research is not related to any matters of concern. Support provided by PT PLN (Persero), PT PLN (Persero) UIT JBB, Midel & Mivolt Fluids Ltd., and Dongnam Petroleum Ind. Co. Ltd. is limited to funding and providing research materials without involvement in research decisions, data analysis, or interpretation of study results.

References

Abdul Hamid, MH, Ishak, MT, Suhaimi, NS, Adnan, J, Makmor, NF, Katim, NIA & Abd Rahman, R 2021, 'Lightning impulse breakdown voltage of rice bran oil for transformer application', *Energies*, vol. 14, no. 16, article 5084, https://doi.org/10.3390/en14165084

Alshehawy, AM, Mansour, DEA & Ghali, M 2019, 'Optical spectroscopy analysis of ester oils under thermal aging conditions', *In:* 2019 IEEE 20th International Conference on Dielectric Liquids (ICDL), pp. 1-4, https://doi.org/10.1109/ICDL.2019.8796836

Amores, G & Virto, M 2019, 'Total and free fatty acids analysis in milk and dairy fat', *Separations*, vol. 6, no. 1, article 14, https://doi.org/10.3390/separations6010014

Bandara, K, Ekanayake, C & Saha, TK 2015, 'Compare the performance of natural ester with synthetic ester as transformer insulating oil', *2015 IEEE 11th International Conference on the Properties and Applications of Dielectric Materials (ICPADM)*, pp. 975–978, https://doi.org/10.1109/ICPADM.2015.7295437

Beroual, A, Sitorus, HBH, Setiabudy, R & Bismo, S 2018, 'Comparative study of AC and DC breakdown voltages in Jatropha methyl ester oil, mineral oil, and their mixtures', *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 5, pp. 1831–1836, https://doi.org/10.1109/TDEI.2018.007219

Bukit, FRA, Zulkarnaen, H & Sormin, RP 2021, 'Mineral mix and soybean oil methyl ester as an alternative to the transformer insulating oil', *In:* 2021 5th International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM), pp. 174–177, https://doi.org/10.1109/ELTICOM53303.2021.9590138

Das, AK 2023, 'Analysis of AC breakdown strength of vegetable oils and effect of mineral oil', *Electric Power Systems Research*, vol. 214, article 108920, https://doi.org/10.1016/j.epsr.2022.108920

Das, AK, Shill, DC & Chatterjee, S 2023, 'Experimental investigation on breakdown performance of coconut oil for high voltage application', *Electric Power Systems Research*, vol. 214, article 108856, https://doi.org/10.1016/j.epsr.2022.108856

Dewi, TIDK, Al-Ghifary, F, Sari, YE, Suwarno & Sulaeman, A 2018, 'The effects of accelerated thermal aging on chemical, electrical, and physical properties of natural ester oil', *In:* 2018 Conference on Power Engineering and Renewable Energy (ICPERE), pp. 1–6, https://doi.org/10.1109/ICPERE.2018.8739665

Dhini, A, Faqih, A, Kusumoputro, B, Surjandari, I & Kusiak, A 2020, 'Data-driven fault diagnosis of power transformers using dissolved gas analysis (DGA)', *International Journal of Technology*, vol. 11, no. 2, pp. 388-399, https://doi.org/10.14716/ijtech.v11i2.3625

Dombek, G & Gielniak, J 2018, 'Fire safety and electrical properties of mixtures of synthetic ester/mineral oil and synthetic ester/natural ester', *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 5, pp. 1846–1852, https://doi.org/10.1109/TDEI.2018.007223

Duanaputri, R, Prasojo, RA, Hakim, MF, Wijaya, B, Widianto, G, Astuti, W, Gallant, RH & Razaan, GTA 2024, 'Comparative analysis of breakdown voltage value and color scale of natural ester oil with mineral oil Shell Diala-B', *In:* 2024 International Conference on Technology and Policy in Energy and Electric Power (ICTPEP), pp. 336–339, https://doi.org/10.1109/ICT-PEP63827.2024.10732899

Dumitran, LM, Gorun, F, Nicolae, S & Mirica, C 2019, 'Dielectric properties of mineral and vegetable oils mixtures for power transformers', *In:* 2019 11th International Symposium on Advanced Topics in Electrical Engineering (ATEE), pp. 1–6, https://doi.org/10.1109/ATEE.2019.8724883

Emara, MM, Mansour, D-EA & Azmy, AM 2017, 'Mitigating the impact of aging byproducts in transformer oil using TiO2 nanofillers', *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 6, pp. 3471–3480, https://doi.org/10.1109/TDEI.2017.006586

Erwantono, H, Permadi, B & Basuki, P 2020, 'Advantages for Indonesia to process coconut oil as power transformer insulation and its cooling system', *In:* 2020 International Conference on Technology and Policy in Energy and Electric Power (ICT-PEP), pp. 152–155, https://doi.org/10.1109/ICT-PEP50916.2020.9249946

Gengadevi, K & Madavan, R 2023, 'Aging analysis of non-edible natural ester oil–paper insulation under various conditions', *Industrial Crops and Products*, vol. 205, article 117528, https://doi.org/10.1016/j.indcrop.2023.117528

Goscinski, P, Nadolny, Z, Tomczewski, A, Nawrowski, R & Boczar, T 2023, 'The influence of heat transfer coefficient α of insulating liquids on power transformer cooling systems', *Energies*, vol. 16, no. 6, article 2627, https://doi.org/10.3390/en16062627

Hadi, MHH, Ker, PJ, Lee, HJ, Leong, YS, Hannan, MA, Jamaludin, MZ & Mahdi, MA 2021, 'Color index of transformer oil: A low-cost measurement approach using ultraviolet-blue laser', *Sensors*, vol. 21, no. 21, article 7292, https://doi.org/10.3390/s21217292

Hamid, MHA, Ishak, MT, Suhaimi, NS, Adnan, J, Hashim, NI, Ariffin, M, Katim, NIA & Abd Rahman, R 2022, 'Electrical properties of palm oil and rice bran oil under AC stress for transformer application', *Alexandria Engineering Journal*, vol. 61, no. 11, pp. 9095–9105, https://doi.org/10.1016/j.aej.2022.02.049

IEEE 2018, *IEEE guide for acceptance and maintenance of natural ester insulating liquid in transformers,* IEEE Std C57.147-2018, Piscataway, NJ, https://doi.org/10.1109/IEEESTD.2018.8438588

Jacob, J, Preetha, P & Krishnan, ST 2020, 'Review on natural ester and nanofluids as an environmental friendly alternative to transformer mineral oil', *IET Nanodielectrics*, vol. 3, no. 2, pp. 33–43, https://doi.org/10.1049/iet-nde.2019.0038

Jayyid, UL, Fadillah, A, Kurniawan, M, Suwarno, Rachmawati, Lesmana, A, Mutia, S & Anwar, A 2024, 'Comparative study of mineral oil, synthetic ester, and natural ester as liquid insulation in transformers', *In:* 2024 6th International Conference on Power Engineering and Renewable Energy (ICPERE), pp. 1–6, https://doi.org/10.1109/ICPERE63447.2024.10845535

Jeong, H, Lee, S, Park, JY, Ryu, J & Bae, CY 2024, 'A study on the insulation breakdown voltage according to degradation condition of natural ester oil', *In:* 2024 IEEE Electrical Insulation Conference (EIC), pp. 300–303, https://doi.org/10.1109/EIC58847.2024.10579102

Kamhoua, A, Mengata Mengounou, G, Monkam, L & Moukengue Imano, A 2024, 'Contribution to the use of palm kernel oil methyl esters as liquid bio-insulators in distribution transformers: Experimentation and simulation of heat transfer', *Results in Engineering*, vol. 22, article 102316, https://doi.org/10.1016/j.rineng.2024.102316

Kano, T, Suzuki, T, Oba, R, Kanetani, A & Koide, H 2012, 'Study on the oxidative stability of palm fatty acid ester (PFAE) as an insulating oil for transformers', *In:* 2012 IEEE International Symposium on Electrical Insulation, pp. 22–25, https://doi.org/10.1109/ELINSL.2012.6251418

Karaman, HS, Mansour, DEA, Lehtonen, M & Darwish, MMF 2023, 'Condition assessment of natural ester–mineral oil mixture due to transformer retrofilling via sensing dielectric properties', *Sensors*, vol. 23, no. 14, article 6440, https://doi.org/10.3390/s23146440

Khan, SA, Tariq, M, Khan, AA & Alamri, B 2021, 'Effect of iron/titania-based nanomaterials on the dielectric properties of mineral oil, natural and synthetic esters as transformers insulating fluid', *IEEE Access*, vol. 9, pp. 168971-168980, https://doi.org/10.1109/ACCESS.2021.3131538

Kiran, SR, Mariprasath, T, Basha, CH, Murali, M & Reddy, MB 2022, 'Thermal degrade analysis of solid insulating materials immersed in natural ester oil and mineral oil by DGA', *Materials Today: Proceedings*, vol. 52, pp. 315–320, https://doi.org/10.1016/j.matpr.2021.09.015

Lyutikova, M, Korobeynikov, S, Mohan Rao, U & Fofana, I 2022, 'Mixed insulating liquids with mineral oil for high voltage transformer applications: A review', *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 29, no. 2, pp. 454-461, https://doi.org/10.1109/TDEI.2022.3157908

Malde, J, teNyenhuis, E & Solie, K 2023, 'Experience in retrofilling of mineral insulating liquid filled transformers with ester liquids', *In:* 2023 IEEE IAS Petroleum and Chemical Industry Technical Conference (PCIC), pp. 59–66, https://doi.org/10.1109/PCIC43643.2023.10414310

Martin, D, Lelekakis, N, Wijaya, J & Williams, K 2013, 'Water uptake rates of transformer paper insulation impregnated with vegetable oil', *IEEE Electrical Insulation Magazine*, vol. 29, no. 5, pp. 56-61, https://doi.org/10.1109/MEI.2013.6585857

Maulida, A, Zahrati, Z, Kamila, H, Mukhriza, T, Gani, A & Supardan, MD 2020, 'Intensification of synthesis of fatty acid isopropyl ester using microwave', *International Journal of Technology*, vol. 11, no. 3, pp. 492-500, https://doi.org/10.14716/ijtech.v11i3.3513

McNeil, MA, Karali, N & Letschert, V 2019, 'Forecasting Indonesia's electricity load through 2030 and peak demand reductions from appliance and lighting efficiency', *Energy for Sustainable Development*, vol. 49, pp. 65–77, https://doi.org/10.1016/j.esd.2019.01.001

Mohamad, N, Azis, N, Jasni, J, Ab Kadir, M, Yunus, R & Yaakub, Z 2018, 'Ageing study of palm oil and coconut oil in the presence of insulation paper for transformers application', *Materials*, vol. 11, no. 4, article 532, https://doi.org/10.3390/ma11040532

Mustangin, M, Purwantana, B, Hidayat, C & Radi 2024, 'Development of high free fatty acid crude palm oil as a biodegradable electrical liquid insulator as an alternative to mineral oil-based insulators', *Cleaner Engineering and Technology*, vol. 18, article 100712, https://doi.org/10.1016/j.clet.2023.100712

Ning, Y, Fan, H, Tang, Z, Xu, Y, Wang, F & Zhang, X 2024, 'Thermal properties of mixtures of synthetic ester/mineral oil and synthetic ester-retrofitted transformer', *In:* 2024 IEEE International Conference on High Voltage Engineering and Applications (ICHVE), pp. 1–4, https://doi.org/10.1109/ICHVE61955.2024.10676086

Oparanti, SO, Rao, UM & Fofana, I 2023, 'Natural esters for green transformers: Challenges and keys for improved serviceability', *Energies*, vol. 16, no. 1, article 61, https://doi.org/10.3390/en16010061

Ortiz, A, Delgado, F, Ortiz, F, Fernández, I & Santisteban, A 2018, 'The aging impact on the cooling capacity of a natural ester used in power transformers', *Applied Thermal Engineering*, vol. 144, pp. 797–803, https://doi.org/10.1016/j.applthermaleng.2018.08.049

Othman, NA, Zainuddin, H, Yahaya, MS, Azis, N, Ibrahim, Z & Musni, MAC 2023, 'Evaluation of total acid number (TAN) of synthetic ester retrofilled oil and its correlation with FTIR spectroscopy', *In:* Proceedings of 2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS 2023), pp. 282–286, https://doi.org/10.1109/ICHVEPS58902.2023.10257322

Pramono, WB, Wijaya, FD, Hadi, SP, Indarto, A & Wahyudi, MS 2024, 'Power transformer load noise model based on backpropagation neural network', *International Journal of Technology*, vol. 15, no. 5, pp. 1550-1560, https://doi.org/10.14716/ijtech.v15i5.5548

Qian, Y, Fan, H, Lin, J, Wang, Q, Zhao, Y, Li, Z & Pan, S 2023, 'Performance analysis of insulating liquids for synthetic ester retrofilling mineral oil transformer', *In:* 2023 2nd Asia Power and Electrical Technology Conference (APET), pp. 208–211, https://doi.org/10.1109/APET59977.2023.10489831

Qin, C, Lin, W, Huang, Y, Liang, H & Hua, H 2024, 'Study on thermal aging insulation characteristics of transformer oil-paper insulation', *In:* 2024 IEEE 4th International Conference on Power, Electronics and Computer Applications (ICPECA), pp. 744–748, https://doi.org/10.1109/ICPECA60615.2024.10471095

Rafiq, M, Shafique, M, Azam, A, Ateeq, M, Khan, IA & Hussain, A 2020, 'Sustainable, renewable and environmental-friendly insulation systems for high voltages applications', *Molecules*, vol. 25, no. 17, article 3901, https://doi.org/10.3390/molecules25173901

Raof, NA, Yunus, R, Rashid, U, Azis, N & Yaakub, Z 2019, 'Effect of molecular structure on oxidative degradation of ester-based transformer oil', *Tribology International*, vol. 140, article 105852, https://doi.org/10.1016/j.triboint.2019.105852

Ravulapalli, S, Kunta, R & Ramamoorty, M 2019, 'Preparation, characterization and feasibility analysis of methyl ester of *Sesbania* seeds oil (MESSO) as alternate liquid dielectrics in distribution transformers', *RSC Advances*, vol. 9, no. 6, pp. 3311–3319, https://doi.org/10.1039/C8RA08378A

Rouabeh, J, M'barki, L, Hammami, A, Jallouli, I & Driss, A 2019, 'Studies of different types of insulating oils and their mixtures as an alternative to mineral oil for cooling power transformers', *Heliyon*, vol. 5, no. 3, article e01159, https://doi.org/10.1016/j.heliyon.2019.e01159

Rozga, P 2013, 'Properties of new environmentally friendly biodegradable insulating fluids for power transformers', *In:* 1st Annual International Interdisciplinary Conference (AIIC 2013), Azores, *Portugal*, pp. 358–364

Rozga, P, Beroual, A, Przybylek, P, Jaroszewski, M & Strzelecki, K 2020, 'A review on synthetic ester liquids for transformer applications', *Energies*, vol. 13, no. 23, article 6429, https://doi.org/10.3390/en13236429

Rozhentcova, N, Galyautdinova, A, Khayaliev, R, Udaratin, AV & Ilyashenko, S 2020, 'Automated diagnostic system for power transformers using a QR code', *International Journal of Technology*, vol. 11, no. 8, pp. 1519-1527, https://doi.org/10.14716/ijtech.v11i8.4540

Samikannu, R, Antony Raj, R, Murugesan, S, Venkatachary, SK & Stonier, AA 2022, 'Assessing the dielectric performance of *Sclerocarya birrea* (marula oil) and mineral oil for eco-friendly power transformer applications', *Alexandria Engineering Journal*, vol. 61, no. 1, pp. 355–366, https://doi.org/10.1016/j.aej.2021.06.002

Scatiggio, F, Camp, G, Actis, R & Tumiatti, V 2023, 'A validated practice for transformer retrofilling', *In:* 2023 IEEE 22nd International Conference on Dielectric Liquids (ICDL), pp. 1–5, https://doi.org/10.1109/ICDL59152.2023.10209334

Scatiggio, F, Pepe, F, Sacco, S & Serafino, C 2019, 'Increased loadability of transformers immersed in natural ester', *In:* 2019 IEEE 20th International Conference on Dielectric Liquids (ICDL), pp. 1–4, https://doi.org/10.1109/ICDL.2019.8796759

Senthilkumar, S, Karthick, A, Madavan, R, Arul Marcel Moshi, A, Sundara Bharathi, SR, Saroja, S & Sowmya Dhanalakshmi, C 2021, 'Optimization of transformer oil blended with natural ester oils using Taguchi-based grey relational analysis', *Fuel*, vol. 288, article 119629, https://doi.org/10.1016/j.fuel.2020.119629

Sharma, P, Agarwal, R, Uppal, A, Narasimhan, CS, Beldar, SS & Velandy, J 2020, 'Effect of aromatics and polar contaminant of natural ester oil on dielectric strength and breakdown time in mineral oil under lightning impulse voltage excitations', *In:* 2020 IEEE 9th Power India International Conference (PIICON), pp. 1–5, https://doi.org/10.1109/PIICON49524.2020.9113010

Shill, DC, Das, AK & Chatterjee, S 2022, 'Lightning impulse breakdown performance of saturated vs unsaturated vegetable oil and their mixtures with mineral oil', *Industrial Crops and Products*, vol. 184, article 115044, https://doi.org/10.1016/j.indcrop.2022.115044

Sibuea, EB & Suwarno 2022, 'Correlation of oil dielectric characteristics, dissolved gases, and operating life to insulation paper degradation of 150 kV power transformers', *In:* 2022 International Seminar on Intelligent Technology and Its Applications (ISITIA), pp. 360–364, https://doi.org/10.1109/ISITIA56226.2022.9855342

Siddique, A, Yaqoob, M, Aslam, W, Zaffar, F, Atiq, S & Usama Shahid, M 2024, 'A systematic review on promising development of cost-effective, biodegradable, and environment friendly vegetable based nanofluids as a future resource for green transformer insulation oil', *Journal of Molecular Liquids*, vol. 403, article 124836, https://doi.org/10.1016/j.molliq.2024.124836

Song, H, Chen, Y, Huang, Q, Yang, L & Wang, T 2024, 'Physicochemical and dielectric properties of natural ester retrofilled mineral oil transformer liquid', *In:* 2024 7th International Conference on Energy, Electrical and Power Engineering (CEEPE), pp. 111–115, https://doi.org/10.1109/CEEPE62022.2024.10586419

Soni, R & Mehta, B 2023, 'A review on transformer condition monitoring with critical investigation of mineral oil and alternate dielectric fluids', *Electric Power Systems Research*, vol. 214, article 108954, https://doi.org/10.1016/j.epsr.2022.108954

Spohner, M, Klampar, M & Liedermann, K 2013, 'Electrical properties of natural oils and methyl esters of their constitutive fatty acids', *In:* 2013 IEEE Electrical Insulation Conference (EIC), pp. 383–386, https://doi.org/10.1109/EIC.2013.6554272

Suriaini, N, Arpi, N, Syamsuddin, Y & Supardan, MD 2021, 'Use of crude glycerol for glycerolysis of free fatty acids in crude palm oil', *International Journal of Technology*, vol. 12, no. 4, pp. 760-769, https://doi.org/10.14716/ijtech.v12i4.4165

Suzuki, T, Oba, R, Kanetani, A, Kano, T, Tamura, T, Kato, M, Watanabe, S, Kasahara, Y & Iwahashi, M 2011, 'Consideration on the relationship between dielectric breakdown voltage and water content in fatty acid esters', *In:* 2011 IEEE International Conference on Dielectric Liquids, pp. 1–4, https://doi.org/10.1109/ICDL.2011.6015424

Tokunaga, J, Nikaido, M, Koide, H & Hikosaka, T 2019, 'Palm fatty acid ester as biodegradable dielectric fluid in transformers: A review', *IEEE Electrical Insulation Magazine*, vol. 35, no. 2, pp. 34–46, https://doi.org/10.1109/MEI.2019.8636104

Villarroel, R, García de Burgos, B & García, DF 2021, 'Moisture dynamics in natural-ester filled transformers', *International Journal of Electrical Power and Energy Systems*, vol. 124, article 106172, https://doi.org/10.1016/j.ijepes.2020.106172

Wada, J, Ueta, G, Okabe, S & Amimoto, T 2013, 'Inhibition technique of transformer insulating oil degradation: Evaluation of the effectiveness of oxidation degradation inhibitors', *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 5, pp. 1641–1648, https://doi.org/10.1109/TDEI.2013.6633694

Wang, F, Ouyang, L, Song, C, Yang, Z, Li, S, Xu, Y & Li, J 2023, 'Enhancing dielectric and thermal performances of synthetic-ester insulating oil via blending with natural ester', *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 3, pp. 1115–1124, https://doi.org/10.1109/TDEI.2023.3243158

Wei, B, Wang, Y, Ren, S, Wang, R & Xu, Y 2020, 'Overload investigation on retrofilling mineral oil distribution transformer with soybean-based natural ester', *In:* 2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE), pp. 1–4, https://doi.org/10.1109/ICHVE49031.2020.9279714

Xue, S, Hou, K, Zhang, Z, Liu, H, Zhu, C, Liu, X & He, M 2021, 'General models for prediction densities and viscosities of saturated and unsaturated fatty acid esters', *Journal of Molecular Liquids*, vol. 341, article 117374, https://doi.org/10.1016/j.molliq.2021.117374

Ye, Z, Wu, K, Cheng, C & Song, W 2017, 'Replacement of aging power transformers considering system risks under multi-level load', *2017 IEEE Power & Energy Society General Meeting*, pp. 1-5, https://doi.org/10.1109/PESGM.2017.8274472

Yoon, H & Chen, G 2021, 'Impact of thermal ageing on space charge characteristics in natural ester oil-impregnated paper', *In:* 2021 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), pp. 23-26, https://doi.org/10.1109/CEIDP50766.2021.9705405

Yu, H, Chen, R, Hu, X, Xu, X & Xu, Y 2017, 'Dielectric and physicochemical properties of mineral and vegetable oils mixtures', *In:* 2017 IEEE 19th International Conference on Dielectric Liquids (ICDL), pp. 1–4, https://doi.org/10.1109/ICDL.2017.8124697

Zhang, Y, Wang, F, Li, S, Zhang, Y, Li, J & Huang, Z 2024, 'Evaluation of basic properties and thermal oxidation aging performance for synthetic ester insulating oils', *In:* 2024 IEEE 7th International Electrical and Energy Conference (CIEEC), pp. 2747–2752, https://doi.org/10.1109/CIEEC60922.2024.10583599

Zheng, H, Liu, C, Cai, S, Yang, T, Feng, Y, Li, X, Wang, Z & Yang, E 2021, 'Investigation of the palm oil-solubility in naphthenic insulating oil using density functional theory and COSMO-RS', *Computational and Theoretical Chemistry*, vol. 1198, article 113184, https://doi.org/10.1016/j.comptc.2021.113184