International Journal of Technology 15(4) 812-823 (2024)

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, University of Indonesia, Depok 16424, Indonesia
[2] Research Center for Biomass Valorizations, University of Indonesia, Depok 16424, Indonesia
[3] Laboratoire de Génie Chimique, Université de Toulouse, CNRS, INPT, UPS, Toulouse, F-31432, France
[4] PT PLN (Persero) Western Java Transmission Main Unit, Depok 16514, Indonesia
(Corresponding author: heri.hermansyah@ui.ac.id; Tel: +62-21-7863516; Fax: +62-21-786 3515

Abstract: Transformers require reliable and eco-friendly oil insulation for long-term operation and sustainability. 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 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 fatty acid 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. 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 IEC 61099 limits, whereas the NEO exceeded 200 ppm after 14 days. SEO with 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, while heavy saturated fatty acids (C20–C24) degraded due to AMO. Additionally, the increase in C12 in SEO contributed to reduced viscosity, potentially affecting oil flow. These findings clarify the role of fatty acid composition and AMO contamination in optimizing transformer oil retrofilling strategies, and support the future adoption of ester-based insulating fluids for more reliable and sustainable power systems.

Keywords: Fatty acid methyl ester; Natural ester; Oil insulation; Retrofilling; Synthetic ester

1. Introduction

Electricity is a fundamental societal need and 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, by the end of 2021,

---

For grants, please provide the grant number and the year it was received. Write it as follows: "This work was supported by the 'Name of organization' funded by 'Name of Grant and number' "

https://doi.org/xx/ijtech.xx
Received date; Revised date; Accepted date

has operated transformers with a total capacity of 155,968 MVA, a sharp increase from 98,897.5 MVA in 2016 (Erwantono et al., 2020). Transformers ensure a reliable and efficient electricity supply in the power transmission system (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% (Ye et al., 2017; Tokunaga et al., 2019). Insulation system degradation 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).

For over 150 years, mineral oil has served as a primary insulating fluid in transformers because of its excellent thermal properties, high efficiency, and cost-effectiveness (Hamid et al., 2022). With its high dielectric strength and low electrical conductivity, mineral oil helps reduce the risk of electrical faults, such as flashovers and sparkovers, and supports heat dissipation to prevent overheating (Lyutikova et al., 2022). Although mineral oil is a popular dielectric fluid, it poses a significant environmental hazard (Rafiq et al., 2020). With a low biodegradation rate of approximately 30% (Soni & Mehta, 2023), these oils are difficult to biodegrade and can contaminate soil and water. A leak or spill of one kilogram of mineral oil can contaminate up to 5 million liters of water (Rozga, 2013; Jacob et al., 2020; Karaman et al., 2023). In addition, mineral oil exhibits limited moisture tolerance, which can lower 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 (Abdul Hamid et al., 2021).

To address the drawbacks associated with mineral oil, Ester-based oils have been suggested as a more sustainable alternative (Soni & Mehta, 2023). Chemically, 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 fatty acid 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 natural esters to absorb and dissolve a much larger amount of water than mineral oils—up to ten times more—since the ester bonds can interact with water molecules through dipole interactions and hydrogen bonding (Martin et al., 2013; Villarroel et al., 2021). 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 the esterification of polyol alcohols (such as pentaerythritol or trimethylolpropane) with fatty acids, typically resulting in molecules with more uniform and branched structures. This molecular design introduces greater steric hindrance around the ester bonds, limiting the number of reactive sites and thereby enhancing resistance to hydrolytic and oxidative degradation. Synthetic esters, such as Midel 7131, Transol Synth 100, and Envirotemp 200, therefore offer lower viscosity, higher fire points, and superior long-term oxidative stability compared to natural esters—making them especially attractive for high-demand transformer applications (Rozga et al., 2020; Oparanti et al., 2023). 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 research related to ester oils is still limited to evaluating certain parameters without considering other factors that could comprehensively affect the long-term performance of insulating oils. A crucial aspect that remains underexplored is how variations in fatty acid profiles affect the efficiency of insulating oils. 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 of palm oil could sustain breakdown voltages near 80 kV despite water concentrations rising from 15 ppm to 50–100 ppm. Simultaneously, moisture inside natural ester oil surged from 43 to 500 ppm, attributed to its unsaturated fatty acid profile, which decreased its breakdown voltage, lowering it from 77 to 60 kV. Research by (Spohner et al., 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. Findings indicate that ester-based insulating fluids, particularly those rich in molecular chains containing multiple double bonds, display a higher tendency toward thermal instability. Similarly, Shill et al. (2022) explored how 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 primarily focused on evaluating how variations in fatty acid profiles influence the preliminary characterization of ester oils, often considering only a limited set of parameters.

Although ester oil offers various advantages, the challenges in its implementation remain significant, mainly related to higher costs than mineral oil and large investments in transformer unit replacement (Rozhentcova et al., 2020). To overcome these obstacles, the retrofilling method—defined as the process of replacing aged mineral oil 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. The standard retrofilling process generally involves draining the old oil, flushing with hot ester oil (minimum 60°C) to dissolve residual mineral oil, replacing all gaskets and seals with compatible materials, degassing, and refilling with new ester oil under vacuum. However, the presence of residual mineral oil remains a major technical concern. It is estimated that 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 fatty acid 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 aged mineral oil with fresh mineral oil, especially in PLN's transformer maintenance activities. However, retrofilling with ester-based insulating oils has not yet been widely implemented and remains at the research and pilot study stage.

Blending different oils enhances the heat tolerance and electrostatic insulation properties of bio-based insulating liquids. Wei et al. (2020) reported that when the residual mineral oil concentration exceeds 7%, the fire resistance of ester oil declines, 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 energy loss in heat. 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, to fill these crucial knowledge gaps, the primary objective of this study is to comprehensively evaluate the simultaneous impact of aged mineral oil (AMO) residue and fatty acid composition on the dielectric and physicochemical performance of both natural (NEO) and synthetic (SEO) ester oils under accelerated thermal aging. 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 future retrofilling policy in Indonesia. The main novelty of this research lies in its in-depth analysis that links macroscopic performance degradation with the underlying transformations in the fatty acid composition profiles. Specifically, this novelty is achieved by intentionally investigating the influence of AMO residue proportions in the critical range of 7.5% and 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

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

Table 1 Specifications of the product data-sheet for natural and synthetic ester oils.

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 research evaluates the role of mineral oil residue and fatty acid distribution in shaping the dielectric characteristics of ester-insulating fluids applied in transformer retrofilling at PT PLN (Persero), as illustrated in Figure 1.

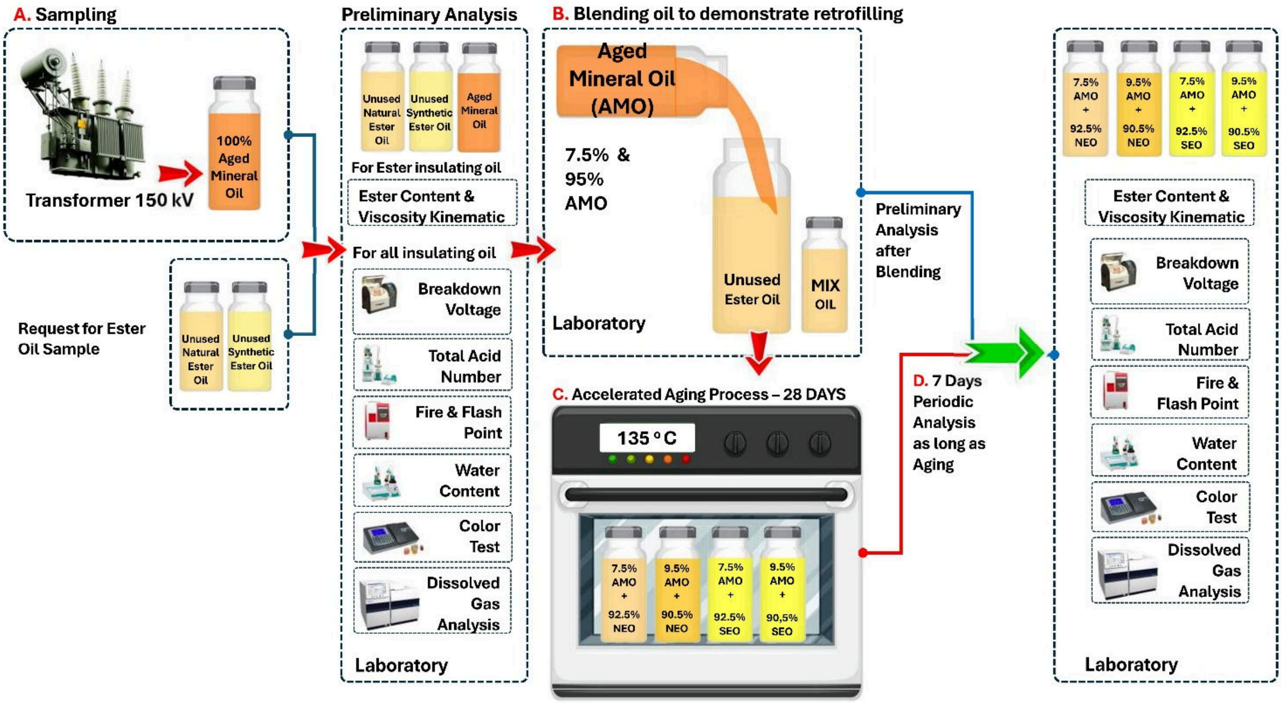


Figure 1 Schematic diagram of the experimental workflow. The process involved four main stages: (a) sampling and preliminary characterization of the base oils (SEO, NEO, and AMO); (b) blending of ester oils with AMO at 7.5% and 9.5% concentrations to simulate retrofilling; (c) accelerated thermal aging 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. *Oil sample preparation*

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

Over a 24-hour period, the Duran glass bottles (1000 mL) were maintained at 110°C after undergoing thorough cleaning and drying to eliminate residual moisture and contaminants. Samples of AMO with SEO or NEO were placed in glass bottles and homogenized using a stirrer for 2 h. The homogenized mixture was then divided into five glass bottles labeled according to 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-based 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, in weeks, the long-term aging and degradation that insulating oils experience over years of real transformer operation.

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

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

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.

The total acceleration factor was then calculated using the doubling rule (Equation 2):

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

where FT is the total time acceleration factor

Following the guidelines outlined in IEC 60216-1:2013 and IEEE Std C57.100™-2011 accelerated aging in this study 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 accelerated aging of 11.02 times against a reference 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 (60–70°C) of power transformers operated by PT PLN (Persero) UITJBB in Indonesia (Wada et al., 2013; Emara et al., 2017; Karaman et al., 2023), ensuring that the accelerated aging protocol is relevant to local field conditions. Using Equations (1) and (2), the calculated factor time (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):

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

where TaTe is the equivalent service life in years, the number of laboratory aging days is the laboratory's duration in days, 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 90–130°C (Emara et al., 2017; Mohamad et al., 2018; Alshehawy et al., 2019; Karaman et al., 2023), but is specifically adapted to reflect actual field conditions in Indonesia. It should also be noted that no metal catalyst was added during the thermal aging process (Das, 2023).

2.2.3. *Measurement, Data Collection, and Processing*

Before aging, the pure insulating oils (SEO, NEO, and AMO) were first subjected to preliminary tests. To evaluate the impact of aging, the samples were examined in five aging periods at 7-day intervals (see Table 2), as done by Gengadevi and Madavan (2023). Furthermore, a quantitative analysis was performed to identify the fatty acid composition of SEO, NEO, and their mixtures, with periodic evaluations conducted at 0, 14, and 28 days. This investigation aimed to determine how different compositions affected 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 (TOL-PLN), the University of Indonesia Department of Chemical Engineering Laboratory (CEDL-UI), and the PT Hyprowira Adhitama Laboratory (HAL).

Table 2. Sample conditions and 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 test equipment.

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

3. Results and Discussion

This section details the results of the accelerated aging experiments and discusses their scientific implications. To provide an initial comparative context, the key findings are summarized alongside relevant literature in Table 4.

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

3.1.1. *Dielectric Strength*

The breakdown voltage (BDV), a critical indicator of dielectric performance, was found to be influenced by the concentration of aged mineral oil (AMO) residue. 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.

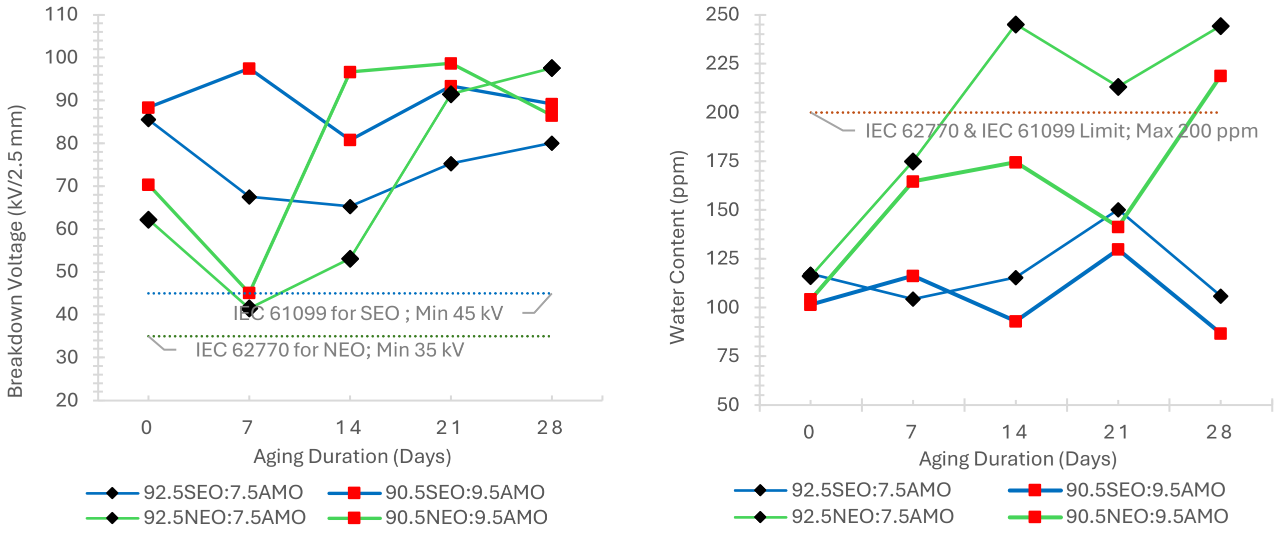
During the initial blending, the BDV of SEO increased from 75.3 kV/2.5 mm (Table 5) to 85.6 and 88.4 kV/2.5 mm with 7.5% and 9.5% AMO, respectively. In contrast, NEO experienced a BDV decrease of 8.09% and 18.79% under the same conditions. This pattern diverges from the general trend reported by Das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

Table 4 Comparative summary of key findings on ester oil-mineral oil blends

Parameters	This Study	Das (2023)	Gengadevi and Madavan (2023)	Wei et al. (2020) & Othman et al. (2023)
Breakdown Voltage (BDV)	Showed an increase for SEO but a decrease for NEO upon initial contamination, highlighting the role of ester structure.	Generally found that mineral oil contamination lowers BDV, but noted a potential increase for saturated esters (coconut oil).	Found a strong correlation between aging and BDV degradation in natural esters, which aligns with our findings for NEO.	Not Reported
Total Acid Number (TAN)	Massive increase in SEO (oxidation-driven); moderate increase in NEO (hydrolysis-driven).	Not Reported		Othman et al. reported a complex, non-linear TAN behavior in mixtures, consistent with our NEO findings.
Viscosity	Remained remarkably stable during aging, suggesting chain scission as the dominant mechanism over polymerization.	Not Reported	Observed a continuous rise in viscosity, indicating that polymerization was the dominant mechanism in their system.	Not Reported
Fire Point	Lost K-class status upon contamination. NEO showed superior stability during aging compared to SEO.	Not Reported	Not Reported	Wei et al. also reported the loss of K-class status when AMO contamination exceeded 7%.
Primary Focus of Study	To link macroscopic degradation with the transformation of fatty acid profiles under specific contamination and aging scenarios.	To compare the AC breakdown strength between different types of natural esters (coconut vs. soybean).	To analyze the aging performance of various non-edible natural esters and their insulation system.	To classify fire safety (Wei) and correlate TAN with FTIR spectroscopy (Othman).

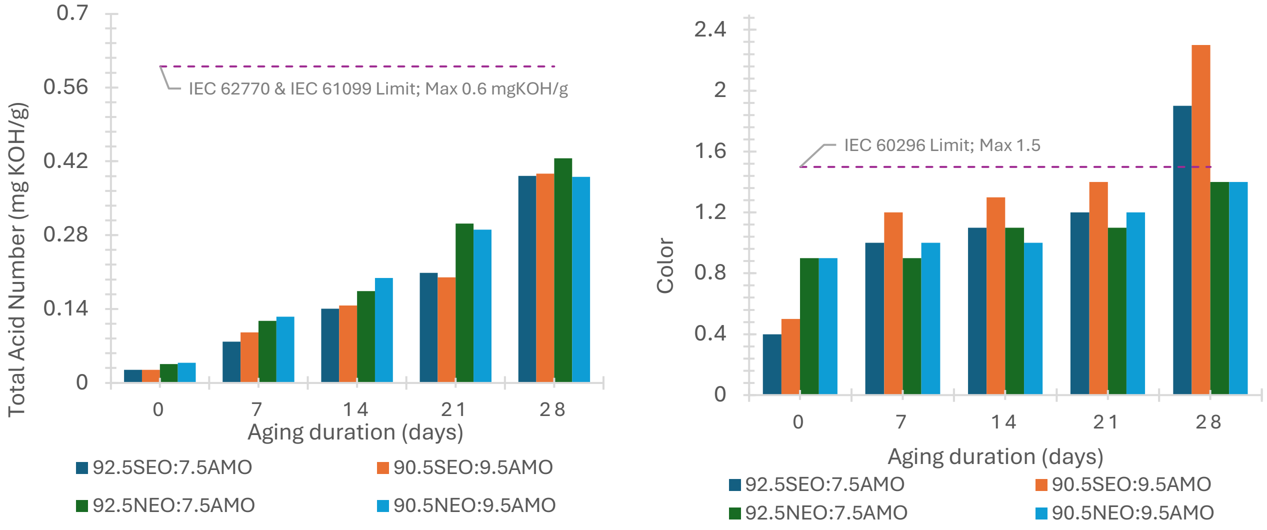
Table 5 Preliminary test results for mineral and ester oils

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	^{o}C	146.33	256.3	226.97
Fire Point	^{o}C	-	316.4	306.4
Kinematic Viscosity [40^{o}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.



(a) (b)

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

Compared to 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 fatty acid profiles and oxidative stability of the tested esters. The observed modifications in the dielectric attributes of ester-based insulating oils can thus 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, analysis indicated that SEO exhibited higher BDV stability than NEO across all AMO concentrations, a result consistent with findings from Khan et al. (2021). Spearman's correlation analysis of SEOs showed a weak relationship between BDV and aging ($\varrho \leq -0.10$), confirming that BDV changes are not strongly influenced by aging time. Conversely, for NEO, BDV showed a moderate to strong correlation with aging ($\varrho \geq 0.6$), which is in agreement with the work of Gengadevi and Madavan (2023).

Regarding moisture content, the relationship with BDV was generally weak ($\varrho \leq 0.10$), consistent with the findings of Khan et al. (2021), Das (2023), Das et al. (2023), but in contrast to of 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 for NEO at 74.33 kV/2.5 mm. 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.

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. One key advantage of ester oil for retrofilling is its 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 polar nature of the ester bonds, 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—compared to 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 (Martin et al., 2013; Villarroel et al., 2021).

Figure 2b illustrates that the moisture levels in SEO remained moderate within the IEC 62770 and IEC 61099 limits (≤ 200 ppm). However, in technical analysis and standard measurement methods, this parameter is often quantified as water content. In this context, NEO exhibited a significant increase in water content during aging, particularly on day 7, with spikes of 245.2 ppm (92.5NEO/7.5AMO on day 14) and 218.8 ppm (90.5NEO/9.5AMO at the end of aging), exceeding standard thresholds. This finding differs from that of Jayyid et al. (2024), who reported that synthetic ester oils exhibited higher moisture content than natural ester oils 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 aged mineral oil 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 natural ester oils tend to absorb more water as the aging period progresses aligns well with the findings of Rouabeh et al. (2019) and Gengadevi and Madavan (2023).

In addition, the oxidative decomposition of the transformer insulating oil 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, and as confirmed by Yoon & Chen (2021), natural esters exhibit a higher tendency to retain moisture than synthetic esters. 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*

Aging due to thermal oxidation is a major factor that accelerates the degradation of insulating oils, including ester-based ones. 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 mgKOH/g for SEO and 0.0354 mgKOH/g for NEO, which are relatively close to 0.0333 mgKOH/g in AMO. The content of carbonyl groups 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, consistent with Bandara et al. (2015), who observed that synthetic esters like Midel 7131 show more rapid TAN escalation compared to natural esters at elevated temperatures. This suggests that the structure and composition of SEO make it more susceptible to acid formation during high-temperature aging, particularly when mixed with AMO.

Interestingly, the increase in TAN in SEO was not strongly correlated with water content ($R^2 < 0$), further supporting the dominance of thermal oxidation 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 are significant contributors to TAN increase in natural esters during aging. This result aligns with Othman et al. (2023), who reported that blends with a lower proportion of mineral oil tend to develop 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, and the effects of oxidation and thermal aging. During operation, oxidative reactions produce carbonyl compounds, peroxides, and dispersed carbon particles that increase the color index and cause a darker color change (Sibuea & 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 SEO from 0.4 to 0.5 to 1.9-2.3. In contrast, NEO increased from 0.9 to 1.4, which is lower than the values reported by Duanaputri et al. (2024) for natural ester oils aged at 150°C for 720 hours (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 color increase of the oil blend. It should be noted that mineral oil typically tends to darken more quickly under oxidation compared to esters, so its presence in the blend can enhance the darkening process. The slow discoloration indicates increased resistance to oxidation and contamination, which extends the oil life and minimizes the need for maintenance. (Hadi et al., 2021). The IEC 62770 standard does not specify a color index limit; however, taking IEC 60296 into consideration, 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, but it serves as a warning for increased oil aging and potential future issues. The oxidative resistance of the oil is predominantly controlled by its inherent chemical structure and the oil fraction used in the blend.

3.1.5. *Flashpoints and fire points*

An insulating oil's ability 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, it is important to see a decrease in these probability values when ester oil is applied during transformer retrofilling. The quantitative analysis in 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, so 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 mixture's flash point 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 overall thermal stability of the blend. Such effects are also reported by Wei et al. (2020) and Qian et al. (2023), 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 about 10°C higher than that of NEO and Midel 7131 tested by Dombek & Gielniak (2018). Although this difference is relatively modest, it highlights the slightly higher thermal stability of SEO. After blending and aging, NEO exhibited better retention of its fire point compared to 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, while SEO averaged 230.37°C, with a smaller difference of 17.43°C. These data indicate that NEO may be more resilient against flash 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. The 90.5NEO/9.5AMO sample experienced a sharp drop in the flash point to 214.3°C on the 14th day of aging due to experimental error. 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.

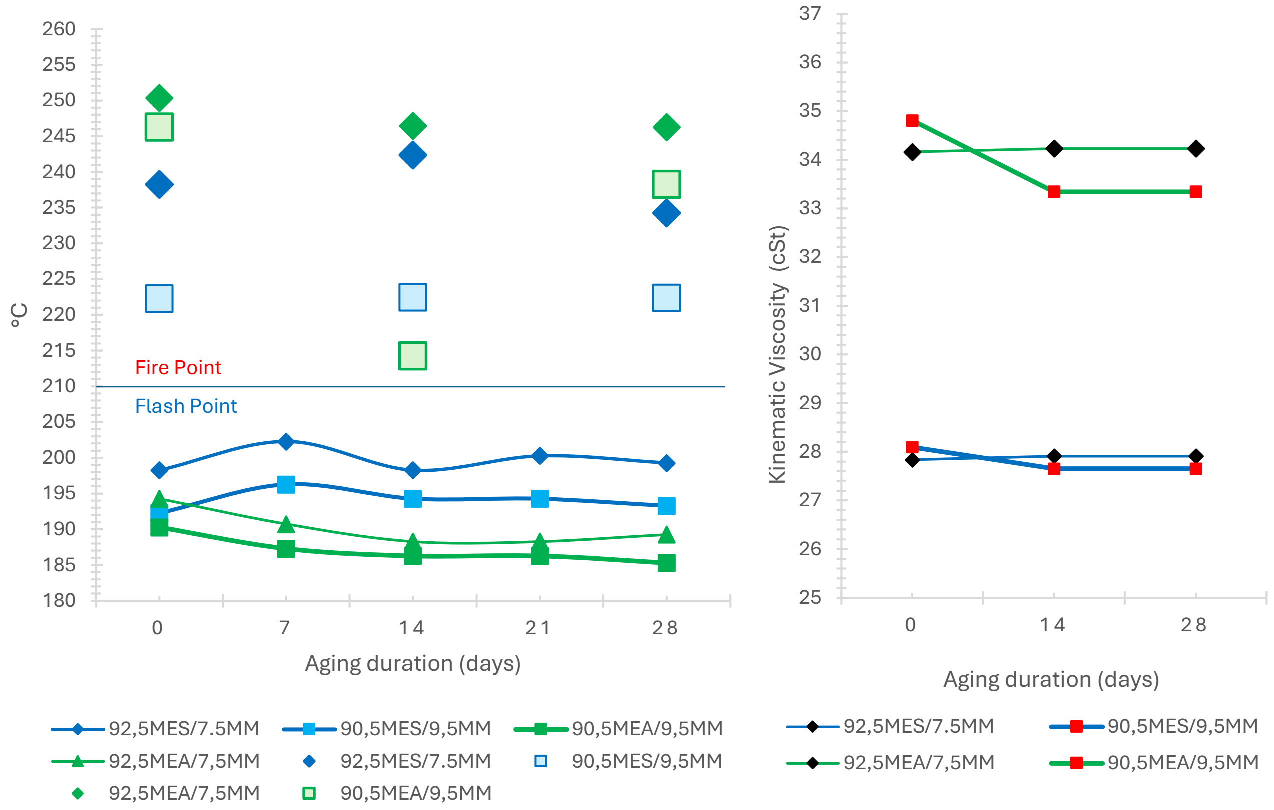
3.1.6. Viscosity

The ability of a transformer to dissipate heat is significantly affected by the properties of its insulating oil, particularly its viscosity. High viscosity can inhibit fluid flow, slow heat dissipation, and increase the operating temperature. The results showed that SEO and NEO at all AMO volume fractions had fairly stable viscosity 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 system's heat dissipation efficiency. This suggests that viscosity stability is not solely dependent on the duration of thermal oxidation but is also influenced by the interaction between ester-based and petroleum-derived oils in the mixture.

This is in contrast to the findings of Ning et al. (2024), who observed a consistent reduction in ester oil viscosity 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 7.5% mineral oil ratio 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 volatility of the hydrocarbon fractions involved.

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 Scatiggio et al. (2019) and Karaman et al. (2023) , 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). Additionally, 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 cSt 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, as 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 globally accepted limits for transformer retrofilling. Thus, the ester oil retrofilling method is feasible.



(a) (b)

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.

Further analysis was conducted to examine the correlation between total acid number (TAN) and viscosity across all aging periods and AMO fractions. Statistical evaluation showed that there was 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 & Madavan (2023) and Scatiggio et al. (2019).

3.2. Effect of Fatty Acid Composition on Ester Oil Performance

3.2.1. Natural ester oil

The quantitative analysis of fatty acids showed that NEO was dominated by $C_{18:0}$ saturated fatty acids (41.79%) and $C_{18:1}$ unsaturated fatty acids (35.43%). The total saturated fatty acid content reached 64.57%, indicating high stability against oxidation (Sharma et al., 2020). Figures 2a and 6 show evidence of how the proportion of monounsaturated fatty acid influences the dielectric characteristics of ester-based insulating oils. The 90.5NEO/9.5AMO sample with a $C_{18:1}$ content of 38.35% had a BDV of 70.4 kV/2.5 mm, whereas the 92.5NEO/7.5AMO sample with a higher $C_{18:1}$ content (40.50%) had a lower BDV (62.2 kV/2.5 mm). This comparison shows a negative relationship between unsaturated fatty acid content and BDV, where a decrease in $C_{18:1}$ 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 incorporating ester-based oil into petroleum-derived insulating oil consistently resulted in reduced viscosity within the blend.

During aging, the saturated fatty acid content remained relatively stable. However, there was a significant decrease in $C_{22:0}$ and $C_{24:0}$ 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. 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, teNyenhuis & Solie, 2023), this study shows a difference. Incompatibility in the solubility 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. C22:0 and C24:0 may segregate or precipitate as microcrystals rather than undergo chemical degradation.

Another interesting phenomenon is the increase in saturated and unsaturated fatty acid levels during aging. 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 free fatty acids (FFA), which originate from hydrolysis and oxidation reactions. However, there was no decrease in $C_{18:1}$ in this study, which should be more susceptible to oxidation than saturated fatty acids. These results pose a challenge in understanding the oxidation stability of natural ester oils. Amores and Virto (2019) reported that the GC-FID method is unable to distinguish between FAME and FFA. Therefore, the increased levels of $C_{18:1}$ and $C_{18:0}$ detected may be due to partial hydrolysis of FAME. It is possible that FFA was converted to FAME (Suriaini et al., 2021) during the test sample preparation.

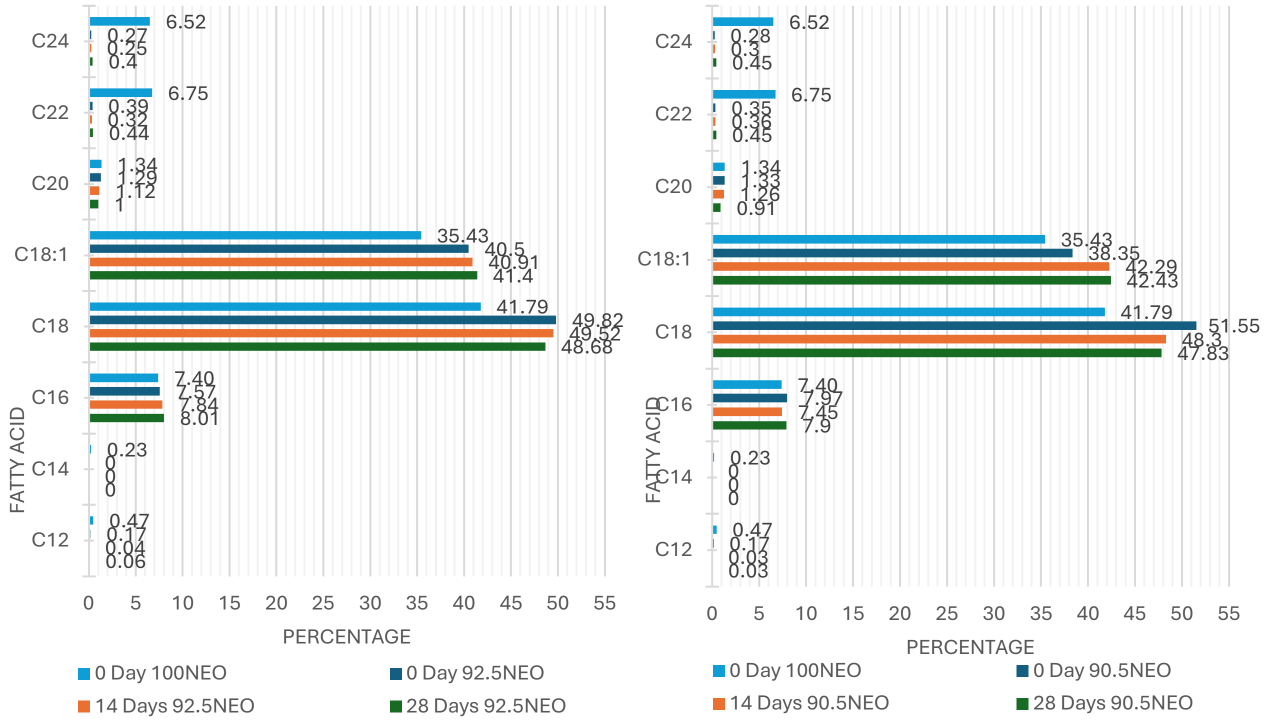
3.2.2. Synthetic Ester Oil

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 (Ravulapalli et al., 2019; Maulida et al., 2020). Regarding its composition, Figure 6 provides an overview of SEO's fatty acid esters, 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, much higher than NEO, with C18 (24.67%) and C22 (21.80%) as the main components, which theoretically provides higher oxidative resistance. However, almost all saturated fatty acid esters in SEO were degraded, except C_{12}, with (C_{20}-C_{24} decreasing to 0%, similar to NEO, while C_{18} in SEO decreased drastically to 94.19%, much greater than NEO. Possibly due to the influence of degradation components in AMO, 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 saturated fatty acid esters.

The transformation of long-chain saturated fatty acids into shorter-chain counterparts is suggested by the increased C12 concentration, which rose 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 cSt to 27.838 cSt, whereas 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 saturated fatty acids, leading to weaker intermolecular forces and improved fluidity within the mixture (Xue et al., 2021).

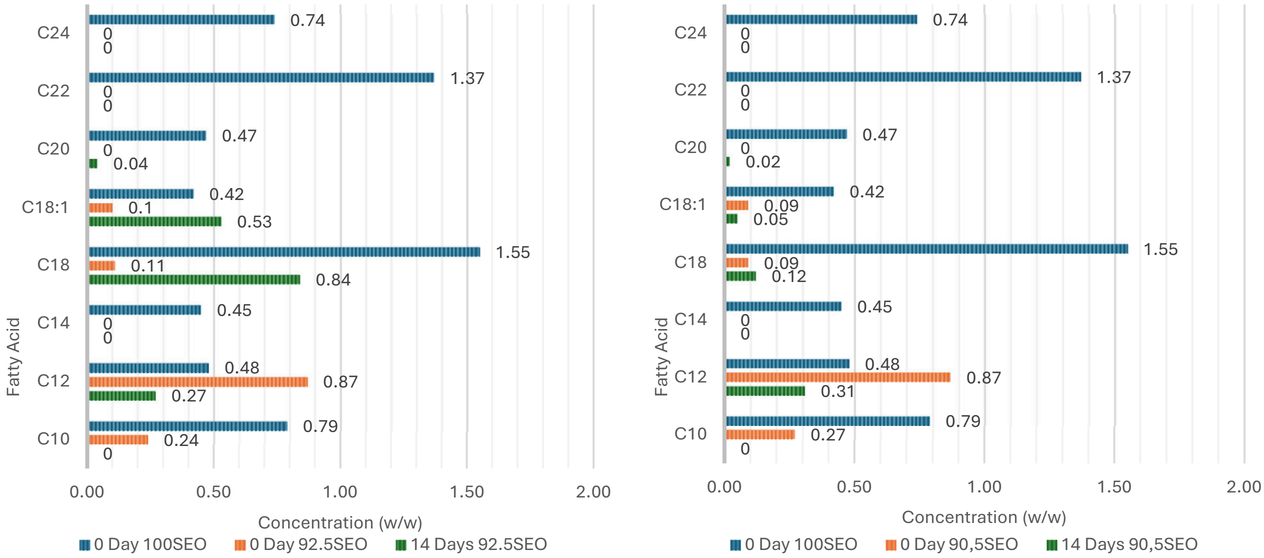
Consistent with this mechanistic perspective, Kamhoua et al. (2024), reported that palm kernel oil methyl ester (PKOME), which features a monoester structure with high lauric acid (C12:0) content, exhibited markedly lower viscosity than both crude palm kernel oil and mineral oil. However, their focus was primarily on the 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 saturated fatty acids—resulting from aging and mineral oil contamination—with observed viscosity reductions in synthetic ester oil blends.

Furthermore, while Kamhoua et al. (2024) emphasized physical and thermal properties, our results extend the discussion by showing that variations in fatty acid composition, such as C18:1 (oleic acid) levels, are also reflected in dielectric breakdown voltage (BDV) performance. For instance, 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 5 Impact of aging on fatty acids in the 92.5NEO/7.5AMO and 90.5NEO/9.5AMO groups



(a) (b)

Figure 6 Fatty acid transformation during the aging process of 92.5SEO/7.5AMO (a) and 90.5SEO/9.5AMO (b)

4. Conclusions

This study confirms the technical viability of retrofilling transformers with both synthetic (SEO) and natural (NEO) ester oils, even in the presence of up to 9.5% aged mineral oil (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. For maximum dielectric strength, a minimal content of unsaturated fatty acids (e.g., C18:1) is paramount, as demonstrated by the superior BDV stability of the highly saturated SEO. 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 while SEO exhibited better resistance to hydrolysis. 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.

For future work, three key avenues are recommended 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 the long-term cost-efficiency benefits of each retrofilling option. Finally, expanding the research to include a wider variety of ester fluids and AMO compositions would help in developing more robust and universal guidelines for the industry.

Acknowledgments

We appreciate 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 would like to 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.

Conflict of Interest

The authors confirm that this research is not linked 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, M.H., Ishak, M.T., Suhaimi, N.S., Adnan, J., Makmor, N.F., Katim, N.I.A. & Abd Rahman, R. 2021. Lightning impulse breakdown voltage of rice bran oil for transformer application. *Energies*. 14(16). DOI: 10.3390/en14165084.

Alshehawy, A.M., Mansour, D.-E.A. & Ghali, M. 2019. Optical Spectroscopy Analysis of Ester Oils under Thermal Aging Conditions. In *2019 IEEE 20th International Conference on Dielectric Liquids (ICDL)*. IEEE. 1–4. DOI: 10.1109/ICDL.2019.8796836.

Amores, G. & Virto, M. 2019. Total and Free Fatty Acids Analysis in Milk and Dairy Fat. *Separations*. 6(1):14. DOI: 10.3390/separations6010014.

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

Beroual, A., Sitorus, H.B.H., 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*. 25(5):1831–1836. DOI: 10.1109/TDEI.2018.007219.

Bukit, F.R.A., Zulkarnaen, H. & Sormin, R.P. 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)*. IEEE. 174–177. DOI: 10.1109/ELTICOM53303.2021.9590138.

Das, A.K. 2023. Analysis of AC breakdown strength of vegetable oils and effect of mineral oil. *Electric Power Systems Research*. 214. DOI: 10.1016/j.epsr.2022.108920.

Das, A.K., Shill, D.C. & Chatterjee, S. 2023. Experimental investigation on breakdown performance of coconut oil for high voltage application. *Electric Power Systems Research*. 214. DOI: 10.1016/j.epsr.2022.108856.

Dewi, T.I.D.K., Al-Ghifary, F., Sari, Y.E., 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)*. IEEE. 1–6. DOI: 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*. 11(2):388. DOI: 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*. 25(5):1846–1852. DOI: 10.1109/TDEI.2018.007223.

Duanaputri, R., Prasojo, R.A., Hakim, M.F., Wijaya, B., Widianto, G., Astuti, W., Gallant, R.H. & Razaan, G.T.A. 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)*. IEEE. 336–339. DOI: 10.1109/ICT-PEP63827.2024.10732899.

Dumitran, L.M., 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)*. IEEE. 1–6. DOI: 10.1109/ATEE.2019.8724883.

Emara, M.M., Mansour, D.-E.A. & Azmy, A.M. 2017. Mitigating the impact of aging byproducts in transformer oil using TiO2 nanofillers. *IEEE Transactions on Dielectrics and Electrical Insulation*. 24(6):3471–3480. DOI: 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)*. IEEE. 152–155. DOI: 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*. 205. DOI: 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*. 16(6). DOI: 10.3390/en16062627.

Hadi, M.H.H., Ker, P.J., Lee, H.J., Leong, Y.S., Hannan, M.A., Jamaludin, M.Z. & Mahdi, M.A. 2021. Color index of transformer oil: A low-cost measurement approach using ultraviolet-blue laser. *Sensors*. 21(21). DOI: 10.3390/s21217292.

Hamid, M.H.A., Ishak, M.T., Suhaimi, N.S., Adnan, J., Hashim, N.I., Ariffin, M., Katim, N.I.A. & Abd Rahman, R. 2022. Electrical properties of palm oil and rice bran oil under AC stress for transformer application. *Alexandria Engineering Journal*. 61(11):9095–9105. DOI: 10.1016/j.aej.2022.02.049.

IEEE. 2018. *IEEE Std C57.147-2018 - IEEE Guide for Acceptance and Maintenance of Natural Ester Insulating Liquid in Transformers*. Piscataway, NJ, USA. DOI: 10.1109/IEEESTD.2018.8438588.

Jacob, J., Preetha, P. & Krishnan, S.T. 2020. DOI: 10.1049/iet-nde.2019.0038.

Jayyid, U.L., 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)*. IEEE. 1–6. DOI: 10.1109/ICPERE63447.2024.10845535.

Jeong, H., Lee, S., Park, J.Y., Ryu, J. & Bae, C.Y. 2024. A Study on the Insulation breakdown voltage according to degradation condition of natural ester oil. In *2024 IEEE Electrical Insulation Conference (EIC)*. IEEE. 300–303. DOI: 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*. 22:102316. DOI: 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*. IEEE. 22–25. DOI: 10.1109/ELINSL.2012.6251418.

Karaman, H.S., Mansour, D.E.A., Lehtonen, M. & Darwish, M.M.F. 2023. Condition Assessment of Natural Ester–Mineral Oil Mixture Due to Transformer Retrofilling via Sensing Dielectric Properties. *Sensors*. 23(14). DOI: 10.3390/s23146440.

Khan, S.A., Tariq, M., Khan, A.A. & 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*. 9:168971–168980. DOI: 10.1109/ACCESS.2021.3131538.

Kiran, S.R., Mariprasath, T., Basha, C.H., Murali, M. & Reddy, M.B. 2022. Thermal degrade analysis of solid insulating materials immersed in natural ester oil and mineral oil by DGA. In *Materials Today: Proceedings*. V. 52. Elsevier Ltd. 315–320. DOI: 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*. 1–1. DOI: 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)*. IEEE. 59–66. DOI: 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*. 29(5):56–61. DOI: 10.1109/MEI.2013.6585857.

Maulida, A., Zahrati, Z., Kamila, H., Mukhriza, T., Gani, A. & Supardan, M.D. 2020. Intensification of Synthesis of Fatty Acid Isopropyl Ester using Microwave. *International Journal of Technology*. 11(3):492. DOI: 10.14716/ijtech.v11i3.3513.

McNeil, M.A., 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*. 49:65–77. DOI: 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*. 11(4):532. DOI: 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*. 18:100712. DOI: 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-Retrofilled Transformer. In *2024 IEEE International Conference on High Voltage Engineering and Applications (ICHVE)*. IEEE. 1–4. DOI: 10.1109/ICHVE61955.2024.10676086.

Oparanti, S.O., Rao, U.M. & Fofana, I. 2023. DOI: 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*. 144:797–803. DOI: 10.1016/j.applthermaleng.2018.08.049.

Othman, N.A., Zainuddin, H., Yahaya, M.S., Azis, N., Ibrahim, Z. & Musni, M.A.C. 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*. Institute of Electrical and Electronics Engineers Inc. 282–286. DOI: 10.1109/ICHVEPS58902.2023.10257322.

Pramono, W.B., Wijaya, F.D., Hadi, S.P., Indarto, A. & Wahyudi, M.S. 2024. Power Transformer Load Noise Model based on Backpropagation Neural Network. *International Journal of Technology*. 15(5):1550. DOI: 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)*. IEEE. 208–211. DOI: 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)*. IEEE. 744–748. DOI: 10.1109/ICPECA60615.2024.10471095.

Rafiq, M., Shafique, M., Azam, A., Ateeq, M., Khan, I.A. & Hussain, A. 2020. DOI: 10.3390/molecules25173901.

Raof, N.A., Yunus, R., Rashid, U., Azis, N. & Yaakub, Z. 2019. Effect of molecular structure on oxidative degradation of ester based transformer oil. *Tribology International*. 140. DOI: 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*. 9(6):3311–3319. DOI: 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*. 5(3):e01159. DOI: 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: AIIC. 358–364. Available: https://scholar.google.com/scholar_lookup?title=Properties+of+new+environmentally+friendly+biodegradable+insulating+fluids+for+power+transformers&author=Rozga,+P.&publication_year=2013&journal=Eur.+Sci.+J.&volume=9&pages=358%E2%80%93364 [2024, June 05].

Rozga, P., Beroual, A., Przybylek, P., Jaroszewski, M. & Strzelecki, K. 2020. A review on synthetic ester liquids for transformer applications. *Energies*. 13(23). DOI: 10.3390/en13236429.

Rozhentcova, N., Galyautdinova, A., Khayaliev, R., Udaratin, A. V. & Ilyashenko, S. 2020. Automated Diagnostic System for Power Transformers using a QR Code. *International Journal of Technology*. 11(8):1519. DOI: 10.14716/ijtech.v11i8.4540.

Samikannu, R., Antony Raj, R., Murugesan, S., Venkatachary, S.K. & Stonier, A.A. 2022. Assessing the dielectric performance of Sclerocarya birrea (Marula oil) and mineral oil for eco-friendly power transformer applications. *Alexandria Engineering Journal*. 61(1):355–366. DOI: 10.1016/j.aej.2021.06.002.

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)*. IEEE. 1–4. DOI: 10.1109/ICDL.2019.8796759.

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)*. IEEE. 1–5. DOI: 10.1109/ICDL59152.2023.10209334.

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

Sharma, P., Agarwal, R., Uppal, A., Narasimhan, C.S., Beldar, S.S. & 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)*. IEEE. 1–5. DOI: 10.1109/PIICON49524.2020.9113010.

Shill, D.C., Das, A.K. & Chatterjee, S. 2022. Lightning impulse breakdown performance of saturated vs unsaturated vegetable oil and their mixtures with mineral oil. *Industrial Crops and Products*. 184. DOI: 10.1016/j.indcrop.2022.115044.

Sibuea, E.B. & 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)*. IEEE. 360–364. DOI: 10.1109/ISITIA56226.2022.9855342.

Siddique, A., Yaqoob, M., Aslam, W., Zaffar, F., Atiq, S. & Usama Shahid, M. 2024. DOI: 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)*. IEEE. 111–115. DOI: 10.1109/CEEPE62022.2024.10586419.

Soni, R. & Mehta, B. 2023. DOI: 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)*. IEEE. 383–386. DOI: 10.1109/EIC.2013.6554272.

Suriaini, N., Arpi, N., Syamsuddin, Y. & Supardan, M.D. 2021. Use of Crude Glycerol for Glycerolysis of Free Fatty Acids in Crude Palm Oil. *International Journal of Technology*. 12(4):760. DOI: 10.14716/ijtech.v12i4.4165.

Suzuki, T., Oba, R., Kanetani, A., Kano, T., Tamura, T., Kato, M., Watanabe, S., Kasahara, Y., et al. 2011. Consideration on the relationship between dielectric breakdown voltage and water content in fatty acid esters. In *2011 IEEE International Conference on Dielectric Liquids*. IEEE. 1–4. DOI: 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*. 35(2):34–46. DOI: 10.1109/MEI.2019.8636104.

Villarroel, R., García de Burgos, B. & García, D.F. 2021. Moisture dynamics in natural-ester filled transformers. *International Journal of Electrical Power and Energy Systems*. 124. DOI: 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*. 20(5):1641–1648. DOI: 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*. 30(3):1115–1124. DOI: 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)*. IEEE. 1–4. DOI: 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*. 341:117374. DOI: 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. In *2017 IEEE Power & Energy Society General Meeting*. IEEE. 1–5. DOI: 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)*. IEEE. 23–26. DOI: 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)*. IEEE. 1–4. DOI: 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)*. IEEE. 2747–2752. DOI: 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*. 1198:113184. DOI: 10.1016/j.comptc.2021.113184.