International Journal of Advances in Applied Sciences (IJAAS)
Vol. 14, No. 4, December 2025, pp. 1393~1401
ISSN: 2252-8814, DOI: 10.11591/ijaas.v14.i4.pp1393-1401

Methods used to enhance the physicochemical properties of natural ester insulating oils for transformers: a review

Muhammad Syahrani Johal[1], Sharin Ab Ghani[1], Mohd Shahril Ahmad Khiar[1], Imran Sutan Chairul[1], Norazhar Abu Bakar[2]
[1]Electrical Asset Condition Monitoring Research Group (e-AMCM), Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[2]Department of Electrical and Electronics Engineering, Universiti Teknologi PETRONAS, Seri Iskandar, Malaysia

Article Info

Article history:

Received Aug 11, 2025
Revised Oct 20, 2025
Accepted Nov 7, 2025

Keywords:

Natural ester insulating oil
Oxidation stability improvement
Physicochemical enhancement
Sustainable transformer insulation
Transformer dielectric fluids

ABSTRACT

Natural ester insulating oils, derived from vegetable-based feedstocks, are increasingly regarded as sustainable alternatives to conventional mineral oils due to their high fire point, biodegradability, and lower environmental impact. However, their widespread adoption in high-voltage equipment is constrained by their inherent limitations, such as lower oxidation stability, higher viscosity, and poor low-temperature performance. In this review, the three principal enhancement strategies developed to address these shortcomings are examined. The use of antioxidants is analysed for its role in improving oxidative resistance and flow characteristics. Transesterification is evaluated as a chemical modification method to alter the molecular structure, thereby enhancing viscosity and thermal stability. Refining and adsorbent treatments are discussed with respect to oil purification and regeneration, emphasising their adsorption efficiency and influence on dielectric performance. A comparative evaluation of these methods highlights their relative effectiveness, scalability, and practical challenges in implementation. This review underscores that no single approach is sufficient, and a combination of different methods is desirable to achieve optimal performance. These insights provide researchers with clear directions for further investigation while offering practitioners a knowledge base to guide the selection and application of enhanced natural ester insulating oils for reliable, long-term transformer operation.

Corresponding Author:

Sharin Ab Ghani
Electrical Asset Condition Monitoring Research Group (e-AMCM)
Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
Email: sharinag@utem.edu.my

1. INTRODUCTION

Insulating oils are widely used in power equipment for the generation, transmission, and distribution of electrical power [1]. Among the examples of power equipment that use insulating oils are bushings, tap changers, circuit breakers, capacitors, paper-insulated lead cables, and transformers [2], [3]. Insulating oil serves as a dielectric coolant to dissipate heat and improve the efficiency of power transformers, traction transformers, instrument transformers, and even special transformers. Numerous studies have been carried out on insulating liquids, and most of these studies are focused on the use of insulating liquids in distribution transformers [4]. This is because a large number of transformer units are used for distribution compared with those used for generation and transmission. Because distribution transformers are installed in residential areas, environmental, safety, and health issues have become a major concern due to the fact that mineral insulating (MI) oils are used as the dielectric liquids in these transformers. In addition, issues on the sustainability of resources and physicochemical properties of MI oils have led scientists and researchers to search for alternative insulating liquids such as silicone oils, synthetic ester oils, mixed liquids, nanofluids, and natural ester insulating (NEI) oils [5]–[9]. NEI oils have gained popularity due to the flammability of MI oils in polychlorinated biphenyls.

Moreover, MI oils were declared as toxic and harmful to the environment by the United States of Health and Human Services in the mid-1970s [2]. NEI oils are basically liquids whose chemical structures are composed of triglycerides. According to the BS EN 62770 (2014) standard, NEI oils for transformers can be divided into two variants: i) unused natural ester or virgin vegetable oil (VVO), mainly composed of triglycerides (where three fatty acids are attached to a glycerol backbone), and ii) low viscosity insulating fluids derived from natural esters (which mainly consist of fatty acid esters or mixtures of triglycerides and fatty acid esters). Fatty acids are categorized into two types: i) saturated fatty acids and ii) unsaturated fatty acids. Saturated fatty acids contain carbon chains without double bonds, whereas unsaturated fatty acids contain carbon chains with one, two, or three double bonds. The unsaturated fatty acids are classified as monounsaturated fatty acids and polyunsaturated (di-unsaturated and tri-unsaturated) fatty acids.

NEI oils are found to be the best candidates to replace MI oils because of their high fire points and flash points, non-toxicity, and good biodegradability. In addition, unlike MI oils, NEI oils do not contain corrosive sulphur, and these oils are hygroscopic fluids with a high level of moisture saturation [10]–[16]. However, NEI oils have poor oxidation stability, higher pour points, low resistance towards lightning impulse, and higher viscosity compared with the standard requirements for insulating oils [17]–[24]. At present, much effort is being made to improve the physicochemical properties of NEI oils. This includes improving the oxidation stability by mixing the NEI oil with antioxidants and reducing the oil viscosity by esterification and adsorbent treatment. These methods are reviewed in more detail in the following sub-sections.

2. METHODS USED TO IMPROVE THE PHYSICOCHEMICAL PROPERTIES OF NEI OILS

The general principles, types, and effects of using antioxidants, chemical modification through transesterification, refining, and adsorbent treatment on the properties of NEI oils are reviewed in this section. These methods are developed to improve the properties of NEI oils, making it possible to prolong the expected lifetime of NEI oils. Each method is discussed in more detail as follows.

2.1. Antioxidants

For the last 50 years, one of the most popular methods to improve the dielectric or physicochemical properties of NEI oils has been by the addition of additives. These include several chemical products which operate as inhibitors, passivators, electron scavengers, and pour point depressants [2]. Their concentration in the oil may vary significantly depending on the additive, ranging from parts per million to several percent. Several studies have shown that the addition of antioxidants enhances the essential properties of NEI oils, such as oxidation stability and dielectric strength. Antioxidant is defined as a radical and hydrogen peroxide scavenger additive that protects various kinds of materials from free radicals and oxidation. Antioxidants have been used in various applications, including pharmaceutical, food safety, packaging, and lubricants. One of the major drawbacks of NEI oils is their low oxidation stability [25]. Oxidation stability is defined as the time taken for oxidative degradation. In general, even though the oxidation process is gradual, it can be hastened by the presence of metal particles, as well as heat and light [26]. The oxidation process can affect the quality and lifetime of NEI oils.

Numerous studies have been carried out to improve the oxidation stability of NEI oils by the addition of antioxidants. The addition of antioxidants can promote the oxidation stability and slow down the oxidation process of NEI oils [27]–[31]. Antioxidants reduce the amount of free radicals, which can generate oxidation reactions and significantly accelerate corrosion [32]. Since the antioxidants remove free radicals, this will significantly reduce corrosion [33]. The enhancement in the properties (e.g., AC breakdown voltage, viscosity, flash point, fire point, and acidity) of NEI oils by the addition of antioxidant mixtures is also reviewed in this section. In general, phenolic antioxidants are most frequently used in vegetable oils and biodiesels owing to their cost, chemical structure, quality, availability, and performance [34]. The addition of phenolic antioxidants such as butylated-hydroxy-anisole (BHA), butylated-hydroxy-toluene (BHT) (also known as 2,6-di-tert-butyl-p-cresol), propyl gallate (PG), tertiary-butyl-hydro-quinone (TBHQ), octyl gallate (OG), dodecyl gallate (DG), pyrogallol (PY), and ethoxyquin (EQ) help promote the oxidation stability of NEI oils [28], [29], [31], [35]. Previous studies pertaining to the properties of NEI oils upon the addition of antioxidant mixtures are summarized in Table 1. It can be seen that the addition of antioxidant mixtures enhances the essential properties of NEI oils for use in power transformers.

Table 1. Properties of NEI oils upon the addition of antioxidant mixtures

Ref.	Antioxidant mixture	Oil	Concentration	Enhancement ratio (%)				
				AC breakdown voltage	Viscosity	Flash point	Fire point	Acidity
[30]	Selenium+ Beta carotene	Sunflower oil	0.5 g selenium+ 0.5 g beta carotene	32.2	-98.1	-	-	100.0
		Mahua oil		-25.1	61.5	-6.7	-7.2	-300.0
		Rice bran oil		-42.9	-22.8	-7.4	-9.9	0.0
		Neem oil		38.8	43.5	-5.2	-4.8	0.0
[31]	BHT+ α-tocopherol	Marula oil	1 g BHT+ 1 g α α-tocopherol	5.3	-7.4 at *RTP	6	3	33.3
[36]	Propyl gallate (PG)+Citric acid (CA)	Rapeseed oil	0.25 wt.% PG+ 0.25 wt.% CA	4.5-6.0	-	-	-	-
[30]	Selenium+TBHQ	Sunflower oil	0.5 g selenium+ 0.5g TBHQ	4.5	-111.6	-	-	0.0
		Mahua oil		-32.0	65.3	3.7	2.8	-200.0
		Rice bran oil		-28.6	-28.1	-14.7	-8.5	-50.0
		Neem oil		25.5	66.7	0.9	-0.8	50.0
[30]	TBHQ+ Beta carotene	Sunflower oil	0.5 g TBHQ+ 0.5 g beta carotene	10.2	-13.7	-	-	-1300.0
		Mahua oil		6.2	67.1	1.9	1.4	-300.0
		Rice bran oil		-28.6	-38.6	-7.4	-5.6	-25.0
		Neem oil		7.5	40.3	5.7	4.4	33.3
[30]	Selenium+ Beta carotene+ TBHQ	Sunflower oil	0.33 g selenium+ 0.33 g beta carotene+0.33 g TBHQ	-14.7	-112.2	-	-	-700.0
		Mahua oil		15	58.7	-	-	0.0
		Rice bran oil		-14.3	-33.3	-11.8	-7.0	-50.0
		Neem oil		-8.0	35.2	10.0	9.6	50.0
[37]	Acetic acid (AA)+Citric acid (CA)	*Terminalia catappa* kernel oil	0.15 wt.% AA+ 0.15 wt.% CA	41.0	11.0	7.8	-	-

*RTP=room temperature

2.2. Transesterification

There are three types of fatty acids, namely, saturated, monounsaturated, and polyunsaturated fatty acids. Each type of fatty acid determines the oil properties (viscosity, acidity, oxidation stability, and electrical properties). Owing to differences in the fatty acid composition, the properties of NEI oils differ from one another. To date, commercial NEI oils based on rapeseed, soybean, castor, sunflower, and palm oils are chemically modified in order to ensure that their properties comply with those set in international standards for oil-immersed power transformers.

The three types of chemical modification methods (transesterification, refining, and treatment with adsorbents) are reviewed in this section. Transesterification is a process of converting triglycerides into diglycerides and then into monoglycerides in the presence of an alkali or acid, producing fatty acid esters and glycerol. Chairul *et al.* [38] conducted transesterification of waste cooking oils with methanol in the presence of an alkali catalyst, potassium hydroxide (KOH), in order to produce transformer insulating oil.

The transesterification process was conducted using the following parameters: i) catalyst concentration: 0.7 wt.%, ii) methanol-to-oil molar ratio: 4:1, iii) reaction time: 48 h, and iv) reaction temperature: 60 °C. The results showed that the color of the oil changed from dark brown to light brown, the acidity reduced from 2.7920 mg KOH/g to 0.2561 mg KOH/g, the kinematic viscosity reduced from 40.84 to 14.19 mm2/s, and the flash point reduced from 269 to 184 °C. Based on the results, the acidity and flash point did not fulfill the requirements stipulated in the IEEE C57.147 standard.

On the other hand, Deraman *et al.* [39] performed transesterification of waste cooking oil with methanol in the presence of an alkali catalyst (NaOH) by mechanical stirring (500 rpm), producing methyl ester. The following settings were used for the transesterification reaction: i) sodium hydroxide (NaOH) catalyst concentration: 0.75 wt.%, and ii) reaction temperature: 60 °C. According to the IEEE C57.147 standard, the acidity of the oil should be less than or equal to 0.06 mg KOH/g. The results showed that the color of the waste cooking oil changed from dark brown to light brown after the transesterification reaction. Sitorus *et al.* [40] produced *Jatropha curcas* methyl ester by transesterification with methanol and KOH.

The reaction parameters used in their work were: i) KOH catalyst concentration: 4.0 wt.%, ii) methanol-to-oil molar ratio: 1:6, iii) reaction time: 4 h, iv) reaction temperature: 63 °C, and v) agitation speed: 400 rpm. The results showed that the acidity reduced from 0.9200-1.5000 mg KOH/g to 0.0708 mg KOH/g, which was slightly higher than the acidity specified in the IEEE C57.147 standard. The physicochemical properties of the *Jatropha curcas* methyl ester complied with the requirements stipulated in the IEEE C57.147 standard, except for the flash point and pour point. The properties of the methyl esters after transesterification discussed in this section are tabulated in Table 2.

Table 2. Properties of three types of methyl ester after transesterification

Property	Waste cooking oil methyl ester (WCOME) [38]	Waste cooking oil methyl ester (WCOME) [39]	*Jatropha curcas* methyl ester (JMEO) [40]	IEEE C57.147™ 2018 standard
Acidity (mg KOH/g)	0.2561	0.2578	0.0708	≤0.06
Colour, ASTM units	-	-	L0.5	≤1.0
Flash point (°C)	184	-	191	≥275
Kinematic viscosity at 40 °C (mm^2/s)	14.19	-	10.45	≤50
Density at 25 °C (g/cm^3)	0.8966	-	0.8960	≤0.96
Pour point (°C)	-28	-	0	≤-10
AC breakdown voltage (kV/mm)	30.0	33.4	87.0	≥20
Water content (mg/kg)	156.40	75.12	64.91	≤200

2.3. Refining

In general, crude vegetable oils extracted from oil seeds have a dark color and contain solid constituents such as proteins and fibers [12]. According to Li *et al.* [41] and Fernández *et al.* [4], the refining process consists of three steps: i) alkali refining, ii) bleaching, and iii) deodorization. These oils are treated to obtain a refined, bleached, and deodorized oil, which is the starting material used to develop a candidate fluid. Next, research made by Beltran *et al.* [42] initiated the use of *Jatropha curcas* oil as a transformer insulating oil. *Jatropha curcas* oil is a non-edible oil extracted from the seeds of the *Jatropha curcas* plant, which is widely found in Mexico. They implemented refining to ensure that the properties of the oil fulfilled the requirements set by international standards for insulating oils. During the refining process, the oil underwent three types of operation: i) acid degumming, ii) chemical neutralization, and iii) bleaching. During acid degumming, the gums were separated from the crude oil by heating the oil with citric acid solution, followed by centrifugation. The process reduced the phospholipids, calcium, magnesium, and iron salt contained in the oil, which improved the oil viscosity, acidity, and fire point by 2, 1, and 1%, respectively. During neutralization, they used NaOH to reduce the free fatty acids in the oil. This process improved the oil viscosity, acidity, and fire point by 2, 90, and 2%, respectively. Finally, they conducted bleaching using bleaching earth and the oil was filtered with a membrane filter to enhance its color and reduce the presence of oxidation by-products and metals. The oil viscosity, acidity, and fire point were improved by 3, 90, and 3%, respectively.

Ghislain *et al.* [43] initiated the use of palm kernel oil as a transformer insulating oil. Palm kernel oil is an edible oil that is widely available in regions with a tropical climate. The refining of crude palm kernel oil has been applied through neutralizing, washing, and drying processes following a previous study by Boyekong *et al.* [44]. During the neutralization process, they used a solution of caustic soda and mixed it with crude palm kernel oil for 5 min to neutralize the free fatty acids present in the oil. Finally, the neutralized oil was washed with distilled hot water and filtered to remove the neutralization sludge. This process improved the acidity and viscosity of the oil by 99.6 and 18.7%, respectively. The color appearance of the crude palm kernel oil also changed from yellow to bright yellow. However, the AC breakdown voltage, flash point, and fire point were reduced to 1.2, 25, and 28.4%, respectively. Das *et al.* [45] investigated the potential of coconut oil as a transformer insulating oil. Matharage *et al.* [46] conducted refining treatments (neutralizing and bleaching) on virgin coconut oil to produce refined coconut oil. They then compared the refined coconut oil to commercial natural esters and mineral oils. This process improved the acidity, viscosity, and flash point of the oil by 97.7, 11.4, and 32.4%, respectively. However, the refining process significantly reduced the AC breakdown voltage of the refined coconut oil by 41.7%.

Chairul *et al.* [47] proposed a similar method to improve the quality of used vegetable oil (UVO). They selected UVO in their research owing to the lack of studies pertaining to the development of UVOs as transformer insulating oils, as well as the higher acidity of these oils compared with other vegetable oils. They implemented a two-step refining process, alkali refining and bleaching. Alkali refining was performed with NaOH (normality: 2.0 N) to produce neutralized UVO and reduce the amount of free fatty acids present in the oil. The oil acidity was the lowest after the alkali refining process, corresponding to a reduction of 94.83% relative to the acidity of the UVO. Next, they applied a two-cycle bleaching process with fuller's earth adsorbent (total concentration: 20 wt.%), and they filtered the oil with a membrane filter to enhance the color and further reduce the acidity of the oil. After the bleaching process, the color rating of the oil was enhanced to L0.5 while the acidity was reduced to 0.1228 mg KOH/g. However, the acidity was still higher than the value stipulated in the BS EN 62770 standard (0.06 mg KOH/g).

Meanwhile, Wu and Zhang [48] introduced alkali refining with KOH in order to reduce the acidity of crude *Jatropha curcas* oil. They optimized the KOH catalyst concentration and time of the refining process. The following KOH catalyst concentrations were considered in their study: 0.0, 0.1, 0.5, 1.0, 3.0, and 5.0 wt.%. The optimum KOH catalyst concentration and alkali refining time were determined based on the acidity of the oil. The acidity reduced from 9.342 to 0.096 mg KOH/g when the KOH catalyst concentration was increased from 0.1 to 1.0 wt.%. Next, the crude *Jatropha curcas* oil was treated using 1 wt.% of KOH and stirred at different refining times (5, 10, 20, 30, 60, and 90 min). In general, the acidity of the oil decreased with an increase in the refining time. The acidity reached its minimum value (0.096 mg KOH/g) when the refining time was 30 min, after which the acidity tended to stabilize. The oil acidity was improved by 99%. Even though the oil acidity reduced from 9.342 to 0.096 mg KOH/g, the acidity was still higher than the value set in the BS EN 62770 standard (0.06 mg KOH/g). The properties of the NEI oils after the refining process, discussed in this section, are presented in Table 3. Based on the results, it can be deduced that to improve the properties of NEI oils, it is best to combine a few chemical modification methods, rather than implementing a single method.

Table 3. Physicochemical and electrical properties of NEI oils after three stages of refining [42], [43], [45], [48]

Refining process	Oil	Insulating oil properties								
		Acidity (mg KOH/g)	Colour	AC breakdown voltage (kV)	Flash point (°C)	Fire point (°C)	Kinematic viscosity at 40°C (mm^2/s)	Moisture content (mg/kg)	Density at 15°C (g/cm^3)	Pour point (°C)
Degumming	*Jatropha curcas* oil	1.5900	-	-	312	354	33.76	-	0.91	−9
	UVO	-	-	-	-	-	-	-	-	-
Neutralization	*Jatropha curcas* oil	0.0100	-	-	328	358	34.01	-	0.91	−9
	UVO	0.2825	L2.0	-	-	-	-	-	-	-
	Jatropha curcas seed oil	0.0960	-	-	-	-	-	-	-	-
	Palm kernel oil	0.05	Bright yellow	76.3	210	240	29.60	-	-	-
	Coconut oil	-	-	-	-	-	-	-	-	-
Bleaching	*Jatropha curcas* oil	0.0400	-	-	330	362	33.47	-	0.91	−9
	UVO	0.1228	L0.5	-	-	-	-	-	-	-
	Palm kernel oil	-	-	-	-	-	-	-	-	-
	Coconut oil	0.0500	-	35	298	-	25.70	-	-	-

2.4. Adsorbents

Abderrazzaq and Hijazi [27] introduced a multi-stage filtration method to enhance the properties of olive oil. The olive oil was processed to pass several tests: AC breakdown voltage, acidity, dissipation factor, moisture content, viscosity, and flash point. Figure 1 shows the three stages involved in the multi-stage filtration method. The method was proven to be successful owing to the number of filtration stages and the use of fuller’s earth absorbent. The acidity of the olive oil was reduced by 70-80% after the third filtration stage, indicating the effectiveness of the method.

Chairul *et al*. [47] devised a different method to reduce the acidity of bleached used cooking oil by adding synthetic silicate adsorbent at a concentration of 15 wt.%. The properties of the oil were evaluated according to the BS EN 62770 standard. They found that the addition of synthetic silicate absorbent maintained the color rating at L0.5 and reduced the acidity of the bleached used cooking oil from 0.1228 to 0.0182 mg KOH/g, which fulfilled the acidity requirement (≤0.06 mg KOH/g). However, the flash point of the oil was still lower than the recommended minimum value of 250 °C specified in the BS EN 62770 standard.

Meanwhile, Čejková [49] studied the removal of acidic substances and the improvement of acidity and properties of natural rapeseed oil through the use of adsorbents. The results showed that the rapeseed oil had a higher moisture content and acidity compared with MI oil. They used simple laboratory filtration devices and adsorbents such as fuller’s earth and basic lumina, which were activated by heat. The addition of fuller’s earth and basic lumina was found to improve the properties of the rapeseed oil, where the acidity reduced from 0.091 to 0.020 mg KOH/g, the moisture content reduced significantly from 87.4 to 44.3 mg/kg, and the dissipation factor enhanced from 0.00477 to 0.00315. However, the AC breakdown voltage of the rapeseed oil reduced from 73.5 to 58.5 kV.

Sari [50] conducted further treatment on an alkyl ester oil (a derivative product of crude palm oil) by adding activated carbon and silica gel adsorbent to improve the properties of the oil. The addition of the activated carbon and silica gel activated by heat at am oil-to-adsorbent ratio of 5:1 significantly improved the ester oil properties, where the acidity reduced from 0.045 to 0.0315 mg KOH/g, the water content significantly reduced from 1383 to 262.3 mg/kg, the AC breakdown voltage increased from 19.08 to 48.5 kV, the viscosity increased from 2.99 to 2.73 mm2/s, and the color rating improved from 0.9 to 0.8. This method clearly shows that the addition of silica gel and activated carbon as adsorbents, followed by a heating process, is recommended as an adsorbent treatment to obtain the optimal chemical, electrical, and physical properties of the alkyl ester oil.

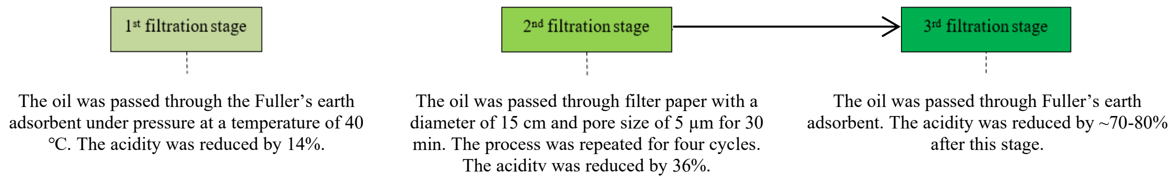

Figure 1. Multi-stage filtration method for olive oil

3. CONCLUSION

NEI oils present a viable and sustainable alternative to MI oils in transformer applications, offering significant advantages in terms of fire safety and environmental compatibility. However, their broader adoption is constrained by limitations in oxidation stability, viscosity, and low-temperature performance. In this review, three key enhancement strategies (additives, transesterification, and adsorbent treatments) have been examined, detailing their mechanisms, benefits, and constraints. Additives can effectively improve oxidative resistance and flow characteristics, transesterification enables molecular modification for better thermal and cold-weather performance, and adsorbent treatment supports purification and regeneration. Even though each method demonstrates specific advantages, the integration of multiple methods offers the greatest potential for achieving high-performance insulating fluids that meet operational and regulatory requirements. Continued research is essential to address the long-term ageing behavior of NEI oils, their compatibility with solid insulation, as well as standardized testing procedures. Advancements in these areas will accelerate the transition towards natural esters as a mainstream dielectric fluid, contributing to safer, more reliable, and environmentally responsible power systems.

ACKNOWLEDGMENTS

The authors wish to thank Ms. Nadia Abdullah from The Golden Touch Language-Editing Service for proofreading this paper.

FUNDING INFORMATION

The authors acknowledge the financial support provided by the Ministry of Higher Education Malaysia, Universiti Teknikal Malaysia Melaka and Universiti Teknologi PETRONAS (OPEX Incentive FY2025 (015LB0-133)).

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Muhammad Syahrani Johal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
Sharin Ab Ghani	✓	✓	✓		✓	✓		✓	✓		✓	✓		
Mohd Shahril Ahmad Khiar	✓	✓		✓		✓	✓	✓	✓	✓	✓			
Imran Sutan Chairul	✓	✓				✓			✓	✓	✓			
Norazhar Abu Bakar	✓								✓		✓			✓

C	:	**C**onceptualization	I	:	**I**nvestigation	Vi	:	**Vi**sualization
M	:	**M**ethodology	R	:	**R**esources	Su	:	**Su**pervision
So	:	**So**ftware	D	:	**D**ata Curation	P	:	**P**roject administration
Va	:	**Va**lidation	O	:	Writing - **O**riginal Draft	Fu	:	**Fu**nding acquisition
Fo	:	**Fo**rmal analysis	E	:	Writing - Review & **E**diting			

CONFLICT OF INTEREST STATEMENT
The authors declare that there are no conflicts of interest that could have influenced the work reported in this paper.

DATA AVAILABILITY
Data availability is not applicable to this paper as no new data were created or analysed in this study.

REFERENCES

[1] M. N. Lyutikova, A. V Ridel, and A. A. Konovalov, “Dielectric liquids: past, present, future (review),” *Power Technology and Engineering*, vol. 57, no. 4, 2023, doi: 10.1007/s10749-024-01709-x.

[2] I. Fofana, “50 years in the development of insulating liquids,” *IEEE Electrical Insulation Magazine*, vol. 29, no. 5, pp. 13–25, 2013, doi: 10.1109/MEI.2013.6585853.

[3] H. Düzkaya, “Applications of natural esters alternative to mineral oils in power transformers,” *Mugla Journal of Science and Technology*, vol. 10, no. 1, 2024, doi: 10.22531/muglajsci.1356778.

[4] I. Fernández, A. Ortiz, F. Delgado, C. Renedo, and S. Pérez, “Comparative evaluation of alternative fluids for power transformers,” *Electric Power Systems Research*, vol. 98, pp. 58–69, 2013, doi: 10.1016/j.epsr.2013.01.007.

[5] S. A. Ghani, N. A. Muhamad, I. S. Chairul, and N. Jamri, “A study of moisture effects on the breakdown voltage and spectral characteristics of mineral and palm oil-based insulation oils,” *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 8, pp. 5012–5020, 2016.

[6] A. Montero, B. García, and C. López, “Life expectancy of transformer paper insulation retrofilled with natural ester in the laboratory,” *Polymers (Basel)*, vol. 15, no. 22, 2023, doi: 10.3390/polym15224345.

[7] H. Zheng, Y. Feng, W. Lv, H. Yang, and X. Li, “Unraveling weak interaction of kinematic viscosity of fatty acid methyl esters in natural ester insulating oils,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 2, 2023, doi: 10.1109/TDEI.2023.3239051.

[8] F. Wang *et al.*, “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, 2023, doi: 10.1109/TDEI.2023.3243158.

[9] C. M. Gutierrez, A. O. Fernandez, C. J. R. Estebanez, C. O. Salas, and R. Maina, “Understanding the ageing performance of alternative dielectric fluids,” *IEEE Access*, vol. 11, 2023, doi: 10.1109/ACCESS.2023.3239895.

[10] R. Asano and S. A. Page, “Reducing environmental impact and improving safety and performance of power transformers with natural ester dielectric insulating fluids,” *IEEE Transactions on Industry Applications*, vol. 50, no. 1, pp. 134–141, 2014, doi: 10.1109/TIA.2013.2269532.

[11] T. V. Oommen, “Vegetable oils for liquid-filled transformers,” *IEEE Electrical Insulation Magazine*, vol. 18, no. 1, pp. 6–11, 2002, doi: 10.1109/57.981322.

[12] Z. Yang *et al.*, “Optimizing molecular structure for trimethylolpropane ester-insulating oil: achieving high fluidity and stability,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 4, 2023, doi: 10.1109/TDEI.2023.3263822.

[13] S. N. Deepa, A. D. Srinivasan, and K. T. Veeramanju, “Performance analysis of blended neem and olive oil as alternate liquid insulation for power transformers,” *International Journal of Renewable Energy Research*, vol. 13, no. 4, 2023, doi: 10.20508/ijrer.v13i4.13906.g8820.

[14] D. Kanumuri, N. Baruah, A. Kumar, and S. K. Nayak, “Effects of oxidative aging on dielectric strength of natural ester oil under DC voltage stresses,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 4, 2023, doi: 10.1109/TDEI.2023.3277416.

[15] H. Zheng *et al.*, “Investigation on cold flow properties of natural ester insulating oils based on molecular dynamics,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 31, no. 3, 2024, doi: 10.1109/TDEI.2024.3349995.

[16] J. Liu, H. Chen, M. Yang, S. Huang, and K. Wang, “Comparative study of natural ester oil and mineral oil on the applicability of the immersion cooling for a battery module,” *Renewable Energy*, vol. 224, 2024, doi: 10.1016/j.renene.2024.120187.

[17] S. A. Ghani, N. A. Muhamad, Z. A. Noorden, H. Zainuddin, N. A. Bakar, and M. A. Talib, “Methods for improving the workability of natural ester insulating oils in power transformer applications: a review,” *Electric Power Systems Research*, 2017, doi: 10.1016/j.epsr.2017.10.008.

[18] C. H. Li, X. Liang, T. Liu, F. Wang, Z. Huang, and J. Li, “Three-dimensional features of streamers in natural ester insulating oil under lightning impulse voltage,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 31, no. 1, 2024, doi: 10.1109/TDEI.2023.3300816.

[19] X. Hu *et al.*, “Experimental research on deterioration effect of transition metals on natural ester,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 31, no. 1, 2024, doi: 10.1109/TDEI.2023.3294367.

[20] P. Przybylek, “Thermal ageing of dry cellulose paper impregnated with different insulating liquids—comparative studies of materials properties,” *Energies (Basel)*, vol. 17, no. 4, 2024, doi: 10.3390/en17040784.

[21] A. Montero, B. García, and J. C. Burgos, “Electric field distribution in natural-ester retrofilled transformers under AC stress,” *International Journal of Electrical Power and Energy Systems*, vol. 155, 2024, doi: 10.1016/j.ijepes.2023.109549.

[22] H. Yoon, G. Chen, and I. L. Hosier, “Influence of thermal aging on dielectric properties of natural ester oil-impregnated paper,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 3, 2023, doi: 10.1109/TDEI.2023.3268039.

[23] D. M. Srinivasa and U. Surendra, “Investigation of electrical properties of developed indigenous natural ester liquid used as alternate to transformer insulation,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 29, no. 2, 2023, doi: 10.11591/ijeecs.v29.i2.pp609-617.

[24] A. K. Das, "Comparative analysis of AC breakdown properties of Jatropha-based ester and other insulating oils: commercial natural ester, synthetic ester, and mineral oil," *Biomass Conversion and Biorefinery*, vol. 14, no. 23, 2024, doi: 10.1007/s13399-023-04779-5.
[25] A. Raymon, P. Pakianathan, M. P. E. Rajamani, and R. Karthik, "Enhancing the critical characteristics of natural esters with antioxidants for power transformer applications," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 3, pp. 899–912, 2013, doi: 10.1109/TDEI.2013.6518959.
[26] P. Totzauer and P. Trnka, "Different ways to improve natural ester oils," in *13th International Scientific Conference on Sustainable, Modern and Safe Transport (TRANSCOM 2019)*, Slovak Republic: Elsevier B.V., 2019, pp. 29--31 May. doi: 10.1016/j.trpro.2019.07.017.
[27] M. H. Abderrazzaq and F. Hijazi, "Impact of multi-filtration process on the properties of olive oil as a liquid dielectric," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 5, pp. 1673–1680, 2012, doi: 10.1109/TDEI.2012.6311515.
[28] A. K. Domingos, E. B. Saad, W. W. D. Vechiatto, H. M. Wilhelm, and L. P. Ramos, "The influence of BHA, BHT and TBHQ on the oxidation stability of soybean oil ethyl esters (biodiesel)," *Journal of the Brazilian Chemical Society*, vol. 18, no. 2, pp. 416–423, 2007, doi: 10.1590/S0103-50532007000200026.
[29] E. O. Aluyor and M. Ori-Jesu, "The use of antioxidants in vegetable oils - a review," *African Journal of Biotechnology*, vol. 7, no. 25, pp. 4836–4842, 2008, doi: 10.4314/ajb.v7i25.59677.
[30] K. S. Lincy, S. S. Kumar, and M. W. Iruthayarajan, "Examining the properties of natural ester oils with antioxidants and nano powders for power applications," *International Journal of Recent Technology and Engineering*, vol. 8, no. 6, pp. 605–610, 2020, doi: 10.35940/ijrte.e6966.038620.
[31] R. Samikannu, R. A. Raj, S. Murugesan, S. K. Venkatachary, and A. A. Stonier, "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, 2022, doi: 10.1016/j.aej.2021.06.002.
[32] S. S. Kumar, M. W. Iruthayarajan, M. Bakrutheen, and S. G. Kannan, "Effect of antioxidants on critical properties of natural esters for liquid insulations," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 4, pp. 2068–2078, 2016, doi: 10.1109/TDEI.2016.7556480.
[33] M. Karthik, M. W. Iruthayarajan, and M. Bakrutheen, "Investigation of vegetable oil blended with antioxidant," in *IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, Coimbatore, India: IEEE, 2015, pp. 05-07 March. doi: 10.1109/ICECCT.2015.7225935.
[34] K. Varatharajan and D. S. Pushparani, "Screening of antioxidant additives for biodiesel fuels," *Renewable and Sustainable Energy Reviews*, vol. 82, no. 3, pp. 2017–2028, 2018, doi: 10.1016/j.rser.2017.07.020.
[35] Y. Xu, S. Qian, Q. Liu, and Z. Wang, "Oxidation stability assessment of a vegetable transformer oil under thermal aging," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 21, no. 2, pp. 683–692, 2014, doi: 10.1109/TDEI.2013.004073.
[36] P. Totzauer, P. Trnka, J. Hornak, P. Kadlec, and J. Pihera, "Antioxidant variations in the nature ester oil," in *18th International Scientific Conference on Electric Power Engineering, EPE 2017*, Kouty nad Desnou, Czech Republic: IEEE, 2017, pp. 17-19 May. doi: 10.1109/EPE.2017.7967314.
[37] M. C. Menkiti, C. M. Agu, P. M. Ejikeme, and O. E. Onyelucheya, "Chemically improved Terminalia catappa L. oil: a possible renewable substitute for conventional mineral transformer oil," *Journal of Environmental Chemical Engineering*, vol. 5, no. 1, pp. 1107–1118, 2017, doi: 10.1016/j.jece.2017.01.037.
[38] I. S. Chairul, N. A. Bakar, M. N. Othman, S. A. Ghani, and M. N. Deraman, "Development of waste cooking oil methyl ester as potential electrical insulating fluid for power transformer," *ARPN Journal of Engineering and Applied Sciences*, vol. 13, no. 20, pp. 8154–8162, 2018.
[39] M. N. Deraman, N. A. Bakar, N. H. A. Aziz, I. S. Chairul, and S. A. Ghani, "The experimental study on the potential of waste cooking oil as a new transformer insulating oil," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 69, no. 1, pp. 74–84, 2020, doi: 10.37934/ARFMTS.69.1.7484.
[40] H. B. H. Sitorus, R. Setiabudy, S. Bismo, and A. Beroual, "*Jatropha curcas* methyl ester oil obtaining as vegetable insulating oil," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 4, pp. 2021–2028, 2016, doi: 10.1109/TDEI.2016.7556474.
[41] X. Li, J. Li, and C. Sun, "Properties of transgenic rapeseed oil based dielectric liquid," in *Proceedings of the IEEE SoutheastCon 2006*, Memphis, TN, USA: IEEE, 2006, pp. 31 March--02 April. doi: 10.1109/second.2006.1629328.
[42] N. Beltrán, E. Palacios, and G. Blass, "Potential of *Jatropha curcas* oil as a dielectric fluid for power transformers," *IEEE Electrical Insulation Magazine*, vol. 33, no. 2, pp. 8–15, 2017, doi: 10.1109/MEI.2017.7866674.
[43] M. M. Ghislain, O. B. Gerard, T. N. Emeric, and M. I. Adolphe, "Improvement of environmental characteristics of natural monoesters for use as insulating liquid in power transformers," *Environmental Technology and Innovation*, vol. 27, p. 102784, 2022, doi: 10.1016/j.eti.2022.102784.
[44] G. O. Boyekong, G. M. Mengounou, and A. M. Imano, "Comparative evaluation of the thermal aging of solid insulation in mineral oil and methyl ester of palm kernel oil," *Journal of Power and Energy Engineering*, vol. 9, no. 5, pp. 166–183, 2021, doi: 10.4236/jpee.2021.95010.
[45] A. K. Das, D. C. Shill, and S. Chatterjee, "Potential of coconut oil as a dielectric liquid in distribution transformers," *IEEE Electrical Insulation Magazine*, vol. 36, no. 6, pp. 36–46, 2020, doi: 10.1109/MEI.2020.9222633.
[46] B. S. H. M. S. Y. Matharage, M. A. R. M. Fernando, M. A. A. P. Bandara, and G. A. Jayantha, "Performance of coconut oil as an alternative transformer liquid insulation," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 3, pp. 887–898, 2013, doi: 10.1109/TDEI.2013.6518958.
[47] I. S. Chairul, N. A. Bakar, M. N. Othman, S. A. Ghani, M. S. A. Khiar, and M. A. Talib, "Potential of used cooking oil as dielectric liquid for oil-immersed power transformers," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 28, no. 4, pp. 1400–1407, 2021, doi: 10.1109/TDEI.2021.009536.
[48] J. Wu and J. Zhang, "Research and development of natural vegetable insulating oil based on *Jatropha curcas* seed oil," *Energies (Basel)*, vol. 13, no. 17, 2020, doi: 10.3390/en13174319.
[49] A. Čejková, "Natural ester — moisture and acidity issue," in *Conference on Diagnostics in Electrical Engineering (Diagnostika)*, Pilsen, Czech Republic: IEEE, 2016, pp. 06-08 September.
[50] Y. E. Sari, "The making processes of natural ester from palm oil through transesterification reaction for transformer application," in *2nd International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, Denpasar, Indonesia: IEEE, 2019, pp. 01-04 October.

BIOGRAPHIES OF AUTHORS

Muhammad Syahrani Johal was born in Melaka, Malaysia, in 1984. He earned both his BEng (Hons.) degree in Electrical Engineering and MSc degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka in 2008 and 2023. He is serving as a Teaching Engineer at the Faculty of Electrical and Electronic Engineering Technology, Universiti Teknikal Malaysia Melaka. His research focuses on vegetable-based transformer dielectric liquids. He also has experience in consultation work with industries related to electrical installation design. He can be contacted at syahrani@utem.edu.my.

Sharin Ab Ghani received his BEng (Hons.) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka in 2008, MEng degree in Electrical Engineering from Universiti Tenaga Nasional in 2012, and PhD degree in Electrical Engineering from Universiti Teknologi Malaysia in 2019. Currently, he is serving as Senior Lecturer at the Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, and as Head of the Electrical Asset Condition Monitoring (e-AMCM) Research Group. His research interests are centred on high voltage engineering, power equipment condition monitoring, green electrical insulation, design of experiments, and optimisation. To date, his outstanding research works have been published in Web of Science (20) and Scopus (73) indexed journals. He also has experience in consultation work with industries related to electrical installation design, transformer condition assessment, and partial discharge analysis. He can be contacted at sharinag@utem.edu.my.

Mohd Shahril Ahmad Khiar was born in Selangor, Malaysia, in 1984. He received his BSc degree in Electrical and Electronics Engineering from Korea University in 2008, MEng degree in Electrical Engineering from Universiti Tenaga Nasional in 2012, and PhD degree from the University of Southampton, United Kingdom, in 2019. He is currently serving as Senior Lecturer at the Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, and as Deputy Head of Electrical Asset Condition Monitoring (e-AMCM) Research Group. His research interests include high voltage engineering and insulation materials, sensors, condition monitoring for power equipment, and asset management. Since 2013, he has published over 28 refereed conference and journal articles associated with transformer condition monitoring and asset management. He can be contacted at mohd.shahril@utem.edu.my.

Imran Sutan Chairul was born in Kuala Lumpur, Malaysia, in 1984. He received his BEng (Hons.) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka in 2008 and MEng degree in Electrical Engineering from Universiti Tenaga Nasional in 2012. He recently completed his PhD degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka and DEng degree in Life and Materials Systems Engineering from Tokushima University, Japan. His research is focused on vegetable-based transformer dielectric liquids. He can be contacted at imransc@utem.edu.my.

Norazhar Abu Bakar received his BEng. (Hons.) degree in electronics and electrical engineering from Leeds University, UK, MSc. (Eng.) in control systems from Sheffield University, UK, and PhD degree in electrical and computer engineering from Curtin University, Australia. He started his career as an assembly engineer at Toshiba Electronics, Malaysia, and then moved to TNB as a SCADA/DA Project Engineer. Currently, he is a senior lecturer at the Department of Electrical and Electronics Engineering, Faculty of Engineering, Universiti Teknologi PETRONAS. His research interests are condition monitoring, asset management, and artificial intelligence. Since 2013, he has published several articles related to transformer condition monitoring and asset management in IEEE Transactions on Dielectrics and Electrical Insulation and IEEE Electrical Insulation Magazine. He can be contacted via email: norazhar.abubakar@utp.edu.my.