



Lapai Journal of Science and Technology, Vol. 10, No. 1 (2024)

DIRECT CURRENT BREAKDOWN CHARACTERISTICS OF TWO-ELEMENT MIXED OIL FOR POWER TRANSFORMER RETROFILLING

*¹Umar, S., ²Aliyu, A., ³Abdulkadir, A., ⁴Musa, I. & ²Abdelmalik, A. A.

*¹Department of Physics, Ibrahim Badamasi Babangida University, Lapai, Nigeria

²Department of Physics, Ahmadu Bello University, Zaria, Nigeria

³Department of Physics, Federal University of Lafia, Nigeria

⁴Department of Mathematics, Ibrahim Badamasi Babangida University, Lapai, Nigeria

*Correspondence Author's e-mail: sadiqmx@gmail.com/2347030976078

ABSTRACT

Environmental concerns as well as utility advantages of the natural ester in retarding paper insulation ageing makes transformer insulation liquid development from a mixture of natural ester and mineral oil preferable over those of synthetic ester and mineral oil. In the present study, mixed insulation liquid was developed from trans-esterified palm olein and mineral oil (MO). The DC breakdown characteristic was measured using a Glow 28720 DC-High Voltage (HV) generator. The results of the measurement were analysed using the Weibull probability distribution as a statistical tool. The natural ester shows a slightly higher Breakdown Voltage (BDV) compared to the MO with low uncertainty. Blend samples with high natural ester percentage composition with respect to the MO, show greater breakdown voltage values. Two blends with the first composed of 50% palm olein fatty acid methyl ester (POFAME) and 50% MO and the other having 75% POFAME and 25% MO both notably exhibited improvement in BDVs up to 6.3% and 5.7% respectively with respect to the MO. The improved breakdown strength is indicative of the potential implication of safe retrofilling of a transformer initially with mineral oil to methyl ester of palm olein as a natural ester and vice versa. Although the blend show improved breakdown strength compared with MO, further investigation of its physical, thermal and dielectric properties is required for its applicability in high-voltage oil-filled equipment.

Keywords: Dielectric test cell, Leakage current, High Voltage, Shape parameter, Weibull distribution

INTRODUCTION

Power transformers play a vital role in electrical transmission and distribution networks, ensuring efficient energy transfer from high-voltage transmission lines (330 kV, 132 kV, and 33 kV) to lower-voltage distribution lines (33 kV, 11 kV, and 415 V; 220 V single phase and 415 V triple phase) (Adoghe *et al.*, 2023). Proper insulation is essential for the reliable



Lapai Journal of Science and Technology, Vol. 10, No. 1 (2024)

operation of these transformers. Traditionally, mineral oil (MO) combined with cellulose-based paper insulation material has been the primary insulating system in oil-filled power transformers due to its cost-effectiveness and favourable electrical and thermal properties (Nogueira *et al.*, 2022; Oparanti *et al.*, 2022; Pattanadech *et al.*, 2017). However, environmental and fire safety concerns have set off the need for an alternative insulation liquid. Mineral oil is poorly biodegradable and has low flash and fire points (Jacob *et al.*, 2020). Natural ester oil (NEO), offers several competitive advantages over MO. It has higher water saturation levels, which help maintain high breakdown strength even with increased moisture content in the insulation system (Nogueira *et al.*, 2022). Additionally, ester oils exhibit better environmental compatibility and fire safety properties (Oparanti *et al.*, 2022).

A transformer initially filled with MO can be refilled with new MO in case of fault. However, about 20% of the oil originally present in the transformer remains behind in the transformer (Beroual *et al.*, 2017). If such a transformer is to be refilled with a new oil of natural ester type, the potential mixing of the two oil types may affect the functionality of the insulation system of the transformer. Beroual *et al.* (2017) using the Cooper Power Systems, EnvirotempTM FR3TM, reported that an addition of even 20% natural ester would increase the breakdown voltage of MO (Beroual *et al.*, 2017). However, natural esters differ in properties from one another by the difference in their fatty acid composition, fatty acid chain length and the level of unsaturation of the fatty acids (Rodrigues *et al.*, 2006). Hence, the breakdown response from mixing of natural esters of different types with MO can result in different outcomes.

Natural esters such as neem, jatropha, palm, etc. are insulation liquid alternative to MO. They have some competitive advantages over MO; they are bio-degradable which make them environmentally friendly, they have high flash point which makes for better fire safety than MO. Natural ester also has better breakdown strength than MO (Jacob *et al.*, 2020). The use of natural ester as additive in MO could improve its biodegradability, fire point, and breakdown voltage. The dielectric properties such as dielectric dispersion, partial discharge, aging characteristics, loss characteristics, etc. of pure ester oils have been studied extensively by different Researchers (Jacob *et al.*, 2020; Nogueira *et al.*, 2022). However, there is limited research on the behaviour of mixed oil from a combination of natural ester oil and mineral oil. Understanding the DC breakdown characteristics of such mixed oil is crucial for effective transformer insulation systems retrofilling. This is because, when



Lapai Journal of Science and Technology, Vol. 10, No. 1 (2024)

replacing the oil insulation of a transformer with a different oil type, the minimal quantity of the initial oil type that is left in the transformer would potentially mix up with the newly introduced oil type which constitutes a blend. A study of the oil blend would reveal the impact of mixing on the dielectric performance of the resulting oil.

Palm olein is a liquid fraction developed from palm oil. It has high saturated fatty acid content and is composed mainly of oleic, palmitic, and linoleic fatty acids (Lv *et al.*, 2018). Oleic fatty acid-rich natural ester oil shows better oxidation stability in transformer insulation applications (Seemamahannop *et al.*, 2019). Hence palm olein makes are good candidates for transformer retrofilling applications.

This research investigates the effect of retrofilling in a transformer on the dielectric breakdown strength of the oil replacement which would likely contain some amount of the previously loaded in the transformer. The study highlights the effect of the mixing of mineral oil with palm olein ester (natural ester) on the dielectric strength of the resulting mixed liquid insulation performance.

METHODOLOGY

Materials

Palm Olein (Goya oil) was purchased from local dealers in Minna, Mineral Oil (FZE United Arabe Emirate); potassium hydroxide pellets (85%, Molychem, India), methanol (99.5%, GHTECH, Guangdong, China) where obtained from Haddis Chemical Store, Zaria, Nigeria; distilled water was collected from Department of Biochemistry Ahmadu Bello University, Zaria, equipment such as the digital high voltage (HV) generator (Glow 28720), bench digital multi-meter (UNI-T UT803) are available at the Materials Science Laboratories, Department of Physics, Ahmadu Bello University, Zaria.

Experimental Procedures

Trans-esterification of the palm olein

50 g of the purchased palm olein was poured into a 500 ml Erlenmeyer flask along with a magnet stirrer and heated to a temperature of 60°C. 1.8 wt.% KOH were weighed and dissolved in methanol; 6:1 methanol to oil mass ratio. The reaction temperature was maintained at 60°C for 60 minutes. The mixture was then poured into a separating funnel and allowed to separate overnight. The bottom layer was discarded and the upper layer containing the fatty acid methyl ester was collected and washed with warm distilled water



Lapai Journal of Science and Technology, Vol. 10, No. 1 (2024)

four times and then placed in an oven at a temperature of 70°C to remove excess methanol. A sample was collected for FTIR analysis.

Development of two-element mixed Oil

Two-element mixed blend composed of percentage volume fraction of palm olein fatty acid methyl ester and mineral oil was mixed. The methyl ester was mixed with mineral oil in the percentage ratio of 50:50, 75:25, and 25:75 palm olein: mineral oil ester by volume. A total volume of 140 ml was prepared for each blend ratio. Both oils were measured using a measuring cylinder and mixed in a 250 ml beaker placed on a magnetic stirrer. The mixture was heated to a temperature of 60 °C and stirred at 1000 rpm for 30 min.

The developed samples are described in Table 1.

Table 1: Sample description

Sample Code	Description
MO	Mineral oil
POFAME	Palm olein fatty acid methyl ester
PM50:50	50 v% Palm olein methyl ester + 50 v% Mineral oil
PM75:25	75 v% Palm olein methyl ester + 25 v% Mineral oil
PM25:75	25 v% Palm olein methyl ester + 75 v% Mineral oil

DC Breakdown test

The experimental setup is as shown in Figure 1. It is adapted from (Yamuna & Madavan, 2024). The oil samples were poured into a cleansed high-voltage dielectric liquid test cell. The dielectric test cell has an electrode spacing of 2.5 mm following the IEC standard. High voltage was applied to the terminals of the dielectric test cell through a current limiting resistor of 1.0 MΩ (protection resistance) from a high voltage generator (Glow 28720 Digital HV source meter) and the leakage current was observed from a benchtop digital multi-meter (UNI-T UT803) and to identify when the breakdown occurs. The voltage was gradually raised at a step of 1.0 kV until breakdown was reached. The breakdown measurement was conducted for every sample five consecutive times and the average value was taken.

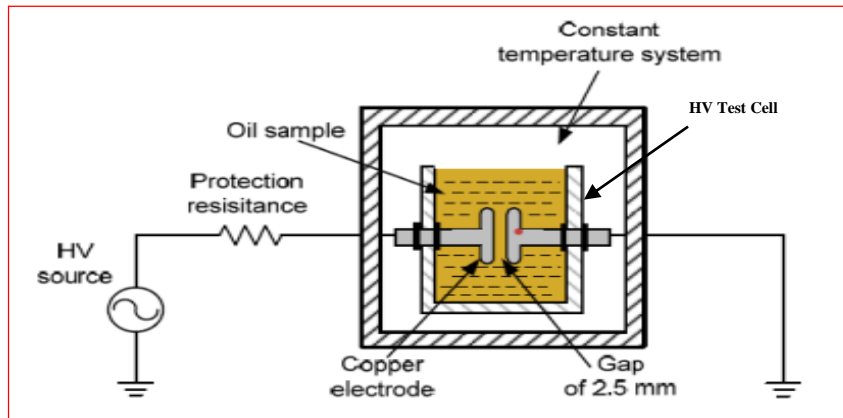


Figure 1: Dielectric Breakdown voltage test set-up (Yamuna & Madavan, 2024)

RESULTS AND DISCUSSION

Fourier Transform Infra-Red (FTIR) Spectrometry of the Palm Olein Methyl Ester

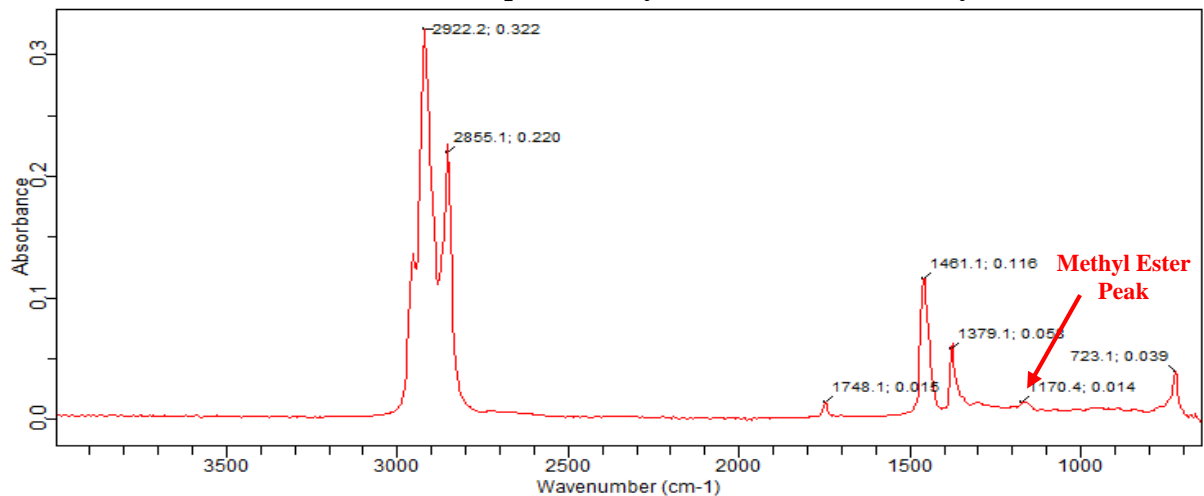


Figure 2: FTIR spectrum of the palm olein methyl ester

The chemical structure of the trans-esterified sample was confirmed through FTIR spectrum analysis. Figure 2 shows the FTIR spectrum of the palm olein. The small peak at 3000.0 cm⁻¹ is the C-H stretching and deformation vibration in unsaturated –HC=CH bonds of the ester (Nosal *et al.*, 2021). There is absence of characteristic weak –C=C– vibrations typically found about 1670-1640 cm⁻¹, which is indicative of minimal unsaturation in the ester



Lapai Journal of Science and Technology, Vol. 10, No. 1 (2024)

sample. The peak at 1748.0 is the typical $-C=O$ ester group which is usually in the range of 1780-1720 cm^{-1} wave number of the FTIR spectrum. The vibration at 1170.4 cm^{-1} is typical of methyl ester functional groups (Abdelmalik, 2014). This confirms the ester formation.

Weibull Statistical Analysis

The Weibull distribution is used to analyse the breakdown characteristics of the dielectric liquid. It allows for the determination of the probability of failure. Linear regression is used to establish the Weibull parameter for the breakdown voltage measured with the digital high voltage (HV) DC generator (Glow 28720). The DC breakdown voltages of the samples were analysed using Weibull statistics. In this analysis, the two-parameter Weibull plot was considered and the breakdown probabilities were determined. The Weibull distribution function $F(x)$ is defined as;

$$F(x) = 1 - \exp\left(\frac{-x}{\alpha}\right)^\beta \quad 1$$

where β is the shape parameter and measures the range of the distribution of the breakdown failure voltages, α is the scale parameter and is the characteristic breakdown voltage i.e. the breakdown voltage at which the cumulative failure probability is 63.2% (Abdelmalik, 2014). The Weibull distributions with $\beta < 1$ have a failure rate that decreases with the variable x , while Weibull distributions with $\beta > 1$ have a failure rate that increases with the variable x (i.e. the breakdown voltage). In breakdown studies of insulation liquids, the failure rate increases with the applied voltage. Hence, β is always greater than 1 (Atiya *et al.*, 2015). The constants can be determined by transforming the equation to a straight line form, and β obtainable from the slope and α from the intercept. Equation 1 can be written as a straight-line equation simply by; re-arranging the terms, then taking the natural log of both sides twice.

$$\ln\left[\ln\left(\frac{1}{1-F(x)}\right)\right] = \beta \ln(x) - \beta \ln(\alpha) \quad 2$$

The gradient and intercept are then determined from the plot of $\ln[\ln(1 - F(x))]$ against $\ln(x)$. Using a sample of n tests, the data can be given rank, r in order of least to highest failure. Then $F(x)$ (i.e. the rate of failure) is estimated using the median ranking method. $F(x)$ is the median rank, then;

$$F(x) = \frac{(r-0.3)}{(n+0.4)} \quad 3$$



Where r is the sequence of data from 1 to N ; N is the number of data, and $0 < F(x) < 1$.

DC Breakdown strength

Table 2. Weibull DC breakdown test parameter with 63.2% probability of failure

Sample	N	Characteristic BDV kV	Shape Parameter (β)	Correlation Coefficient
MO	5	26.8	46.79	0.833
POFAME	5	27.0	34.47	0.927
PM50:50	5	28.5	44.13	0.944
PM75:25	5	28.0	11.20	0.853
PM25:75	5	26.9	47.23	0.876

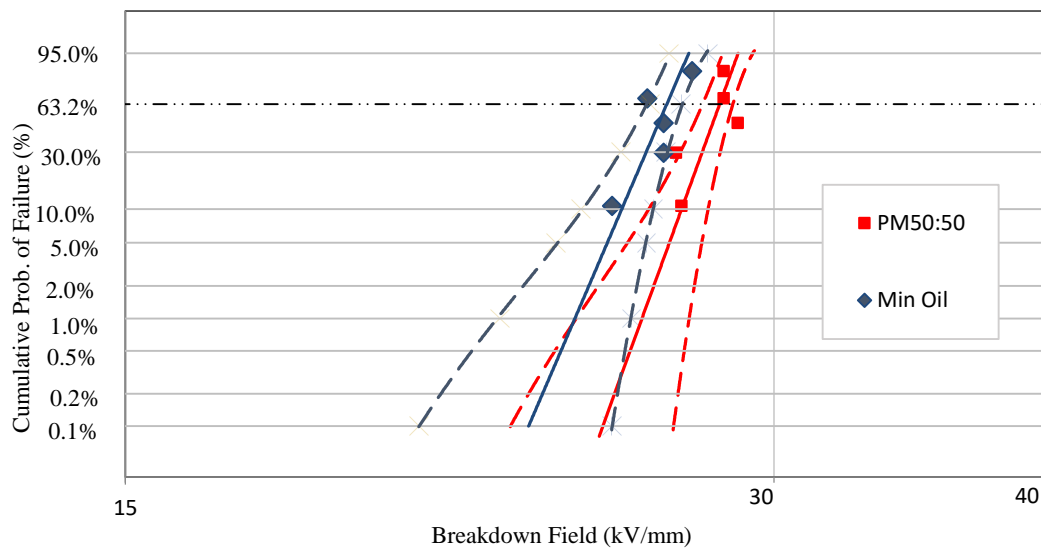


Figure 3: Plot of Weibull distribution of the breakdown field of the optimum blend and Mineral Oil

The breakdown voltages of the samples show higher values than those of Mineral oil (MO). The palm olein fatty acid methyl ester (POFAME) sample had a slightly higher breakdown voltage than those of MO (Table 2). Natural ester typically has a breakdown voltage higher than that of MO (Atalar *et al.*, 2022). The fatty acid molecular composition of the natural ester makes for better moisture tolerance and provides natural esters with comparatively better electro-thermal ageing than MO (Hao *et al.*, 2019). The blend sample of 50% MO and



Lapai Journal of Science and Technology, Vol. 10, No. 1 (2024)

50% POFAME (PM50:50) has the highest DC BDV at 63.2% probability failure, and the Weibull distribution plots in Figure 3 shows how the oil blend compares with the MO. Sample PM50:50 has BDV 6.3% higher than that of MO and 5.6% higher than the ester (POFAME). It has a high value of shape parameter. The large value of the shape parameter is indicative of less uncertainty in the measurement, and the measured BDVs are narrowly distributed (Figure 3). However, the blend sample PM75:25 also shows improved BDV compared to both the POFAME and MO, with a wide distribution of measured breakdown voltages demonstrated by the small value of the shape parameter (see Figure 4). It is indicative of less uncertainty in measurement. The sample with the least percentage of POFAME addition, PM25:75, has the least improvement, only minutely higher than those of MO but not greater than those of POFAME. It can be deduced that blend samples with a higher percentage of natural ester against MO, has the greatest breakdown strength. This can be attributed to the fatty acid composition of the natural ester. Generally, the addition of a high fraction of natural ester of palm olein origin results in breakdown voltage enhancement. This is similar to findings by Beroual *et al.* (2017) (Beroual *et al.*, 2017)

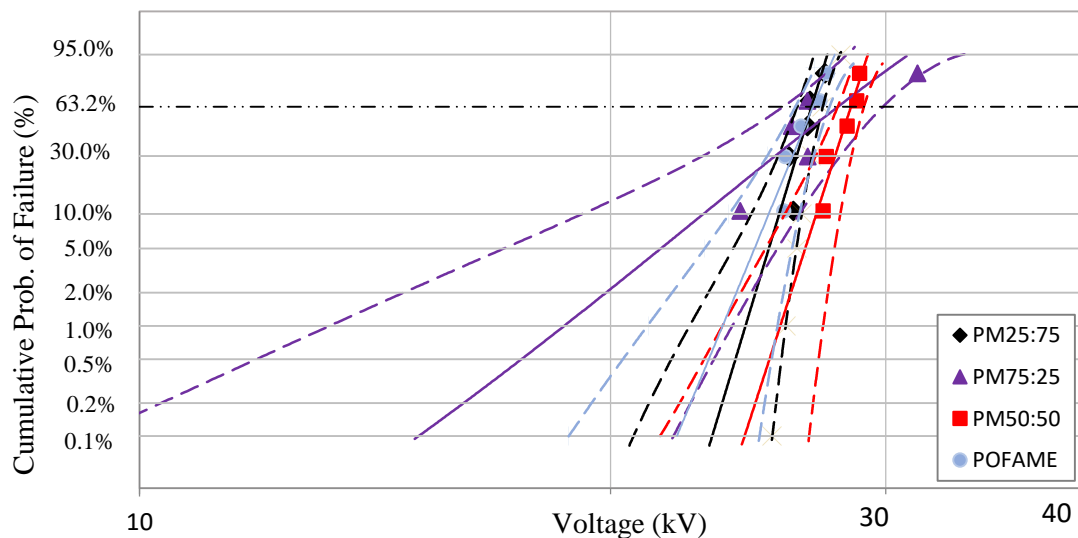


Figure 4: A plot of Weibull distribution of breakdown field of the developed ester and blend



CONCLUSION

The methyl ester of palm olein, POFAME which is a liquid fraction of palm oil (also known as red oil) is developed using potassium hydroxide as an alkaline catalyst. The ester was confirmed by FTIR spectrum analysis. The blends composed of percentage fractions of POFAME and mineral oil (MO) were developed. DC breakdown voltage (BDV) measurement shows higher breakdown voltages in blend samples of high percentage POFAME fractional compositions. There was an improvement of about 6.3% and 5.7% respectively in BDVs with the addition of 50% and 75% POFAME to 50% and 25% MO respectively. The result demonstrates that improvement in breakdown characteristics is potentially possible by refilling a power transformer initially loaded with MO insulation oil with new POFAME oil. A study of other properties of insulation liquid such as dielectric loss, acid value, viscosity and density temperature dependence, thermal capacity would provide more information on the potential workability of the developed oil blend as insulation liquid. The study of the compatibility of the oil with paper insulation of transformer is recommended. This would provide information on the aging behavior of the developed oil blend.

Acknowledgement

The authors wish to thank the management of the materials science laboratories, Department of Physics, Ahmadu Bello University, Zaria for providing the laboratory space and equipment used in this work.

REFERENCES

- Abdelmalik, A. A. (2014). Chemically modified palm kernel oil ester: A possible sustainable alternative insulating fluid. *Sustainable Materials and Technologies*, 1–2, 42–51. <https://doi.org/10.1016/j.susmat.2014.06.001>
- Adoghe, A. U., Adeyemi-Kayode, T. M., Oguntosin, V. & Amahia, I. I. (2023). Performance evaluation of the prospects and challenges of effective power generation and distribution in Nigeria. *Heliyon*, 9(3), e14416. <https://doi.org/10.1016/j.heliyon.2023.e14416>
- Atalar, F., Ersoy, A. & Rozga, P. (2022). Investigation of Effects of Different High Voltage Types on Dielectric Strength of Insulating Liquids. *Energies*, 15(21), 8116. <https://doi.org/10.3390/en15218116>



Lapai Journal of Science and Technology, Vol. 10, No. 1 (2024)

- Atiya, E. G., Mansour, D.-E. A., Khattab, R. M. & Azmy, A. M. (2015). Dispersion behavior and breakdown strength of transformer oil filled with TiO₂ nanoparticles. *IEEE Transactions on Dielectrics and Electrical Insulation*, 22(5), 2463–2472. <https://doi.org/10.1109/TDEI.2015.004742>
- Beroual, A., Khaled, U., Mbolo Noah, P. & Sitorus, H. (2017). Comparative Study of Breakdown Voltage of Mineral, Synthetic and Natural Oils and Based Mineral Oil Mixtures under AC and DC Voltages. *Energies*, 10(4), 511. <https://doi.org/10.3390/en10040511>
- Hao, J., Dan, M., Liao, R. & Li, J. (2019). Effect of Moisture on Particles Accumulation and Oil Breakdown Characteristics in Mineral Oil and Natural Ester Under Non-Uniform DC Electrical Field. *IEEE Access*, 7, 101785–101794. <https://doi.org/10.1109/ACCESS.2019.2930574>
- Jacob, J., Preetha, P. & Thiruthi Krishnan, S. (2020). Review on natural ester and nanofluids as an environmental friendly alternative to transformer mineral oil. *IET Nanodielectrics*, 3(2), 33–43. <https://doi.org/10.1049/iet-nde.2019.0038>
- Lv, C., Wang, Y., Zhou, C., Ma, W., Yang, Y., Xiao, R. & Yu, H. (2018). Effects of dietary palm olein on the cardiovascular risk factors in healthy young adults. *Food & Nutrition Research*, 62(0). <https://doi.org/10.29219/fnr.v62.1353>
- Nogueira, T., Carvalho, J. & Magano, J. (2022). Eco-Friendly Ester Fluid for Power Transformers versus Mineral Oil: Design Considerations. *Energies*, 15(15), 5418. <https://doi.org/10.3390/en15155418>
- Nosal, H., Moser, K., Warzała, M., Holzer, A., Stańczyk, D. & Sabura, E. (2021). Selected Fatty Acids Esters as Potential PHB-V Bioplasticizers: Effect on Mechanical Properties of the Polymer. *Journal of Polymers and the Environment*, 29(1), 38–53. <https://doi.org/10.1007/s10924-020-01841-5>
- Oparanti, S. O., Rao, U. M. & Fofana, I. (2022). Natural Esters for Green Transformers: Challenges and Keys for Improved Serviceability. *Energies*, 16(1), 61. <https://doi.org/10.3390/en16010061>
- Pattanadech, N., Maneerot, S., Jariyanurat, K. & Nimsanong, P. (2017). Electrical characteristic comparison of mineral oil and natural ester for transformer applications.



Lapai Journal of Science and Technology, Vol. 10, No. 1 (2024)

2017 *International Electrical Engineering Congress (iEECON)*, 1–5.
<https://doi.org/10.1109/IEECON.2017.8075764>

Rodrigues, J. D. A., Cardoso, F. D. P., Lachter, E. R., Estevão, L. R. M., Lima, E. & Nascimento, R. S. V. (2006). Correlating chemical structure and physical properties of vegetable oil esters. *Journal of the American Oil Chemists' Society*, 83(4), 353–357. <https://doi.org/10.1007/s11746-006-1212-0>

Seemamahannop, R., Bilyeu, K., He, Y., Kapila, S., Tumiatti, V. & Pompili, M. (2019). Assessment of Oxidative Stability and Physical Properties of High Oleic Natural Esters. *2019 IEEE 20th International Conference on Dielectric Liquids (ICDL)*, 1–6. <https://doi.org/10.1109/ICDL.2019.8796627>

Yamuna, M. & Madavan, R. (2024). Impact of nanoparticles mixtures on mineral and pongamia ester oils dielectric strength. *Biomass Conversion and Biorefinery*, 14(5), 7167–7179. <https://doi.org/10.1007/s13399-022-03235-0>