Pertanika J. Sci. & Technol. 31 (6): 2931 - 2946 (2023)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Short-term Ageing Study on the Palm Oil and Mineral Oil in the Presence of Insulation Paper, Moisture, Low Molecular Weight Acid, and Oxygen

Muhammad Muzamil Mustam[1,2], Norhafiz Azis[2,3]*, Jasronita Jasni[2], Rasmina Halis[4], Mohd Aizam Talib[5], Robiah Yunus[6], Nurliyana Abdul Raof[7] and Zaini Yaakub[8]

[1]*Faculty of Electrical Engineering, Universiti Teknologi MARA, Pasir Gudang Campus, 81750 UiTM, Seri Alam, Pasir Gudang, Johor, Malaysia*
[2]*Advanced Lightning, Power and Energy Research Centre (ALPER), Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*
[3]*Institute of Nanoscience and Nanotechnology (ION2), Universiti Putra Malaysia, 43400 UPM, Sedang, Selangor, Malaysia*
[4]*Department of Natural Resources Industry, Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*
[5]*Advanced Diagnostic Services, TNB Labs Sdn. Bhd., 43000 Kajang, Selangor, Malaysia*
[6]*Department of Chemical and Environmental Engineering, Faculty of Engineering, University Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*
[7]*Department of Chemical Engineering and Energy Sustainability, Faculty of Engineering, Universiti Malaysia Sarawak, 94300 UNIMAS, Kota Samarahan, Sarawak, Malaysia*
[8]*Hyrax Oil Sdn. Bhd. Lot 4937, Batu 51/2, Jalan Meru, Mukim Kapar, 41050 Klang, Selangor, Malaysia*

ABSTRACT

This study presents the short-term ageing study on refined, bleached and deodorised palm oil (RBDPO) and mineral oil (MO) in the presence of insulation paper, moisture, low molecular weight acid (LMA) and oxygen. The ageing experiment was performed for 7 days at 140°C. The oil was maintained dried while the paper's moisture was varied between 0.5% and 3.5%. In total, 0.2 g of LMA and 20 mbar of oxygen pressure were initially introduced in the oil before the ageing started. Several analyses were conducted after the ageing experiment, which include the AC breakdown voltage (BDV) oil/paper, tensile strength, degree of polymerization (DP) and thermogravimetric analysis and differential scanning calorimetry (TGA-DSC). After being subjected to ageing in the

ARTICLE INFO

Article history:
Received: 28 October 2022
Accepted: 06 March 2023
Published: 03 October 2023

DOI: https://doi.org/10.47836/pjst.31.6.16

E-mail addresses:
muhammadmuzamil@uitm.edu.my (Muhammad Muzamil Mustam)
norhafiz@upm.edu.my (Norhafiz Azis)
jas@upm.edu.my (Jasronita Jasni)
rasmina@upm.edu.my (Rasmina Halis)
aizam.talib@tnb.com.my (Mohd Aizam Talib)
robiah@upm.edu.my (Robiah Yunus)
arnurliyana@unimas.my (Nurliyana Abdul Raof)
zaini@hyraxoil.com (Zaini Yaakub)
* Corresponding author

ISSN: 0128-7680
e-ISSN: 2231-8526

presence of LMA and oxygen, the reduction of AC BDV of RBDPO is lower than MO at all moisture levels. At the same condition, the AC BDV of RBDPO-impregnated paper also maintains higher than MO-impregnated paper. The RBDPO-impregnated paper, in the presence of LMA and oxygen, has higher resistance toward ageing than MO-impregnated paper based on DP and tensile index, even in high moisture. All RBDPO are more resistant to ageing than MO in the presence of LMA and oxygen based on the high onset temperatures of the TGA-DSC analysis.

Keywords: Breakdown voltage, degree of polymerization, insulation paper, tensile strength

INTRODUCTION

Recently, vegetable oil (VO) has been identified as a possible substitute for mineral oil (MO) for application in transformers due to its biodegradability, environmental friendliness and fire safety (Maharana et al., 2018; Martin et al., 2006; Matharage et al., 2016; Maharana et al., 2018; Raj et al., 2020; Raymon et al., 2013; Suwarno & Pasaribu, 2017;). Palm oil (PO) is among the most widely accessible VOs in Asian countries (RSPO, 2015; Suryani et al., 2020). Refined, bleached and deodorised palm oil (RBDPO) is one of the common varieties of PO originating from the oil palm fruit (Azis et al., 2014). Different studies are conducted on RBDPO to explore its application as a dielectric insulating fluid (Makmud et al., 2018; Makmud et al., 2019).

The ageing characteristics of MOs are previously examined, which cover the physiochemical and electrical aspects (Abdelmalik, 2015; Carcedo et al., 2015; Coulibaly et al., 2012; Matharage et al., 2016; Munajad et al., 2017; N'cho et al., 2016). Similar studies are carried out for VOs such as coconut, palm, soya, sunflower, rapeseed and corn oils, whereby among the important finding is that the ageing of cellulose insulation can be retarded as a result of its water scavenging and hydrolytic protection mechanisms (Gomna et al., 2019; Rapp et al., 2005; Vihacencu et al., 2013). The ageing can affect the electrical properties of VOs, such as the electrical dissipation factor and resistivity (Ciuriuc et al., 2014; Wilhelm et al., 2011). In addition, the AC breakdown voltage (BDV) of the natural ester can increase up to 30.96 % after being subjected to ageing (Maharana et al., 2019). A previous study shows that most of the acid generated in MO is low molecular weight acid (LMA). The LMA generated in VO is lower than MO (Azis & Wang, 2011). The presence of LMA can further enhance the degradation of paper (Kouassi et al., 2018).

The ageing characteristics of RBDPO are also examined in recent years (Ismail et al., 2013; Kiasatina et al., 2011; Mohamad et al., 2016; Sinan et al., 2014; Suleiman et al., 2014). A previous study revealed that the AC breakdown voltage of aged RBDPO can decrease between 9.8% and 28.2% after being subjected to ageing (Mohamad et al., 2016). Similarly, it is found that the ageing rate of paper aged in MO can be up to 1.6 higher than

RBDPO and coconut oil samples based on previous ageing models (Mohamad et al., 2015). The percentage of reduction of the tensile index (TI) of RBDPO-impregnated paper is lower than that of MO-impregnated paper at the end of the ageing period (Mohamad et al., 2016). The thermogravimetric analysis and differential scanning calorimetry (TGA-DSC) for aged RBDPO reveals that the onset temperature is 408°C while MO is 297°C (Raof et al., 2019). Currently, the study on the effect of ageing accelerators such as moisture, oxygen and acid on the ageing performance of RBDPO is still lacking.

This paper discusses the impact of short-term ageing on the RBDPO and MO in the presence of insulation paper, moisture, acid and oxygen. The type of acid used in the study is LMA. The properties such as AC BDV of the oil/paper, tensile strength, degree of polymerization (DP) and TGA-DSC are measured and analysed. The ageing factor is derived from the influence of different ageing accelerators. The current study provides a fundamental understanding of the RBDPO and MO aged in the presence of ageing accelerators for possible future applications in transformers.

METHODOLOGY

Thermal Ageing Procedure

The MO and RBDPO were initially filtered 3 times using a membrane filter with a pore size of 0.2 µm. The properties and appearances of oils are shown in Figure 1 and Table 1. These oils were dried for 2 days at 85°C in a vacuum oven. All samples were filled with nitrogen to reduce the interaction with oxygen. The final moisture contents of RBDPO and MO were 109 ppm and 12 ppm, respectively. Next, the paper was dried at 90°C or 105°C in a vacuum oven to produce the sample with different moisture contents known as base, low, medium and high moistures. The paper was dried at 105°C for 48 hours, 105°C for 96 hours, 90°C for 48 hours and 90°C for 24 hours to produce base, low, medium and high moisture samples. The final moisture for the base, low, medium and high moisture paper samples are 0.87%, 0.55%, 1.66% and 2.65%. The paper was then impregnated with oils in a vacuum oven for 24 hours at 85°C. These oils were introduced with 0.2 g of formic acid

Table 1
Oil properties

Properties (Unit)	MO	RBDPO
Viscosity, 40°C (mm^2/s)	7.6	21.2
Density, 150°C (kg/m^3)	890	915.5
Flashpoint (°C)	154	320
Water content (mg/kg)	<20	60
Breakdown voltage (kV)	40-60	60-70
Acidity (mg KOH/g)	<0.2	<0.06
Dielectric dissipation factor, 90°C	<0.001	0.03

Figure 1. MO and RBDPO

as LMA and 20 mbar of oxygen pressure above the bottle's oil surface. The oil-to-paper ratio was set to 20:1, with 450 g of oil and 22.5 g of paper, and it was aged in borosilicate glass. The bottle cap reinforced with polytetrafluoroethylene tape was used to seal the borosilicate glass containing the oil and paper, aged for 7 days at 140°C to minimise the environmental interaction.

AC Breakdown Voltage of Oil

An automatic BAUR DPA 75C was used to obtain the AC BDV of oil as per ASTM D1816-12, as shown in Figure 2. The test was conducted at room temperature between 28.4 and 32.9°C (ASTM D1816-12, 2019). The gap spacing between the 36 mm diameter VDE electrodes was fixed to 2.5 mm. In total, 400 ml of oil was carefully poured into the test cell to prevent the formation of any bubbles. The oil was given 15 minutes to rest prior to the test. The voltage was then gradually increased at 0.5 kV/s until the breakdown occurred. Next, the oil was stirred continually using a magnetic stirrer while the interval between breakdowns was set to 5 minutes. In total, 50 measurements of AC BDV were obtained for MO, and the average value was used for the analysis.

AC Breakdown Voltage of Oil Impregnated Paper

The AC BDV of paper was measured using BAUR DPA 75 C as per IEC 60156, as seen in Figure 3. First, the gap distance of the sphere electrodes with a 12.5 mm diameter was set based on the thickness of the oil-impregnated paper. In total, 2 layers of oil-impregnated paper were used due to the measurement limit caused by the very small gap distance based on the thickness of 1 layer of oil-impregnated paper. Next, 400 ml of pre-processed oil was carefully poured into the test cell, whereby the voltage ramping rate was set to 2 kV/s. The oil-impregnated paper was moved to other positions after each of the breakdowns. In total, 20 measurements of AC BDV were recorded for the oil-impregnated paper, whereby the average value was used for the analysis.

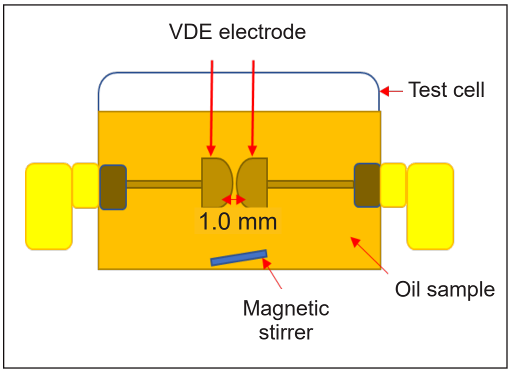


Figure 2. AC breakdown voltage test of oil

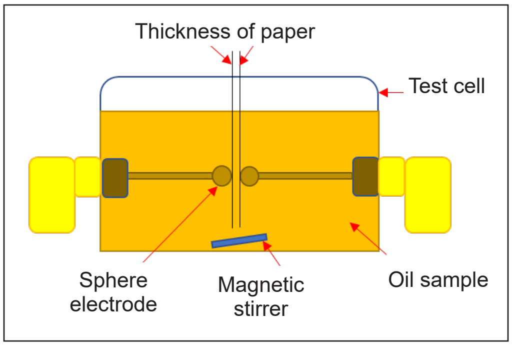


Figure 3. AC breakdown voltage test of oil-impregnated paper

Tensile Strength

Tensile strength was performed using an Instron 5566 model universal testing machine as per BS EN ISO 1924-2. A 10 kN universal testing machine load cell was used, as shown in Figure 4. The crosshead speed and full-scale load range were adjusted to 20 mm/min and 0.5 kN. The distance between the two clamps was set to 100 mm. The paper width and gap distance of the paper were set to 16 mm ± 0.1 mm and 180 mm ± 0.1 mm, respectively. In total, 5 samples were tested for each type of paper and the average value was used for the analysis. Next, the maximum load of TI was calculated based on Equation 1.

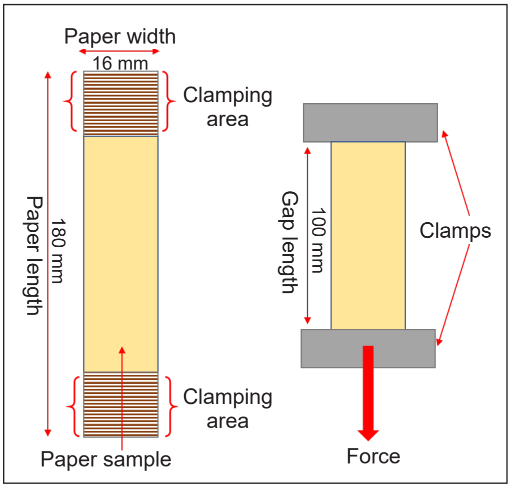


Figure 4. Tensile strength test of paper

$$\mathrm{TI} = ((\bar{\mathrm{F}}/\mathrm{W})\ /\mathrm{G}) \times 10^3 \quad [1]$$

Whereby TI is the paper's tensile index in Newton's metres per gram, $\bar{\mathrm{F}}$ is the maximum load in Newton, W is the paper's width in millimetres, and G is the paper's grammage in grams per square metre. The paper's grammage under study was around 51.8 g/m^2.

Acidity

The acidity of the oils was determined using a Metrohm 877 oil Titrano plus as per ASTM D974 (2023). For each type of oil, 10 g was utilised for the measurement, as seen in Figure 5. In total, 1 measurement was obtained for each type of oil.

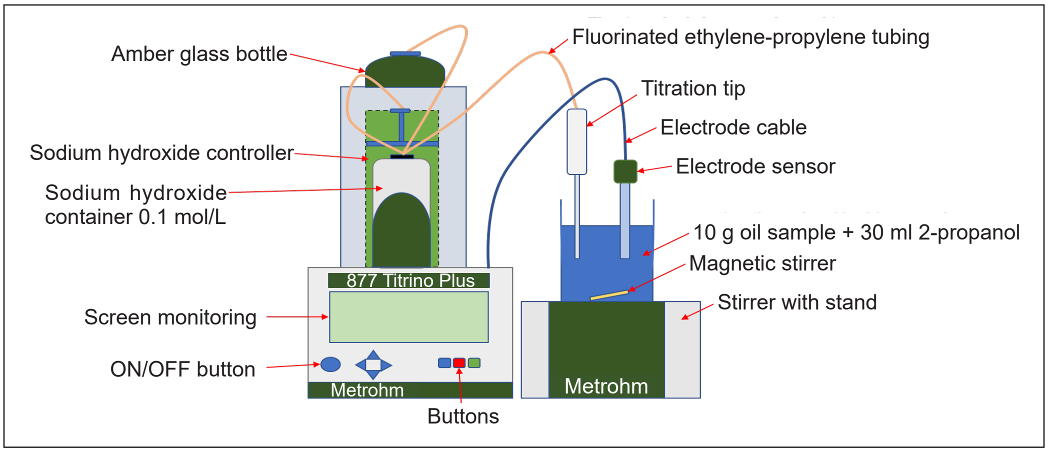


Figure 5. Acidity test of oil

Moisture in Oil and Paper

A Metrohm 831 Karl Fischer (KF) Coulometer was used to measure the moisture in oil based on ASTM D6304 (2021). For each type of oil, 1 ml of oil was used for the moisture measurement, as shown in Figure 6. A Metrohm 774 Karl Fischer Coulometer measured the moisture content of the insulation paper according to IEC 60814. The moisture in the paper was extracted via an oven technique. The total weight of paper used for the moisture measurement is 0.5 g, as seen in Figure 7. In total, 2 moisture measurements were taken for RBDPO and MO for the insulation paper, where the average value was used for the analysis.

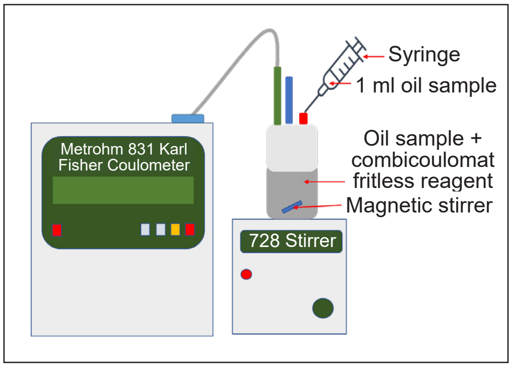


Figure 6. Moisture content test of oil

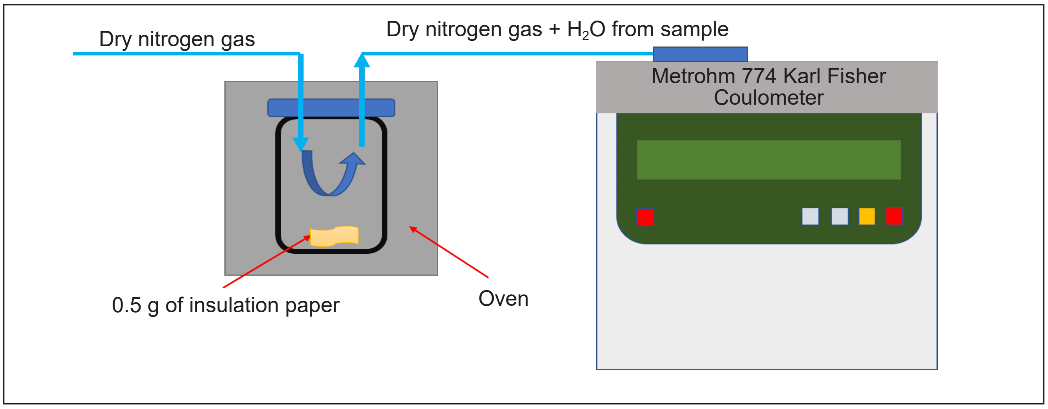


Figure 7. Moisture content test of paper

Thermogravimetric and Differential Scanning Calorimetry Analysis

The measurements of the oils were performed under non-isothermal conditions based on the standard TGA from Mettler Toledo, TGA-DSC HT 3, as shown in Figure 8. The weight of the oil used was 5 mg. The system was first purged with nitrogen gas at 50 ml/min for around 20 minutes at 25°C to release the trapped gases. The sample was then heated from 25°C to 600°C at a steady rate of 10°C/min, and the temperature was maintained for 10 minutes.

Degree of Polymerization

The DP of the paper was obtained based on the average intrinsic viscosity according to ASTM D4243 (2023), as seen in Figure 9. The residual oil was removed from the paper through soxhlet extraction using hexane for up to 8 hours to obtain the dry weight value.

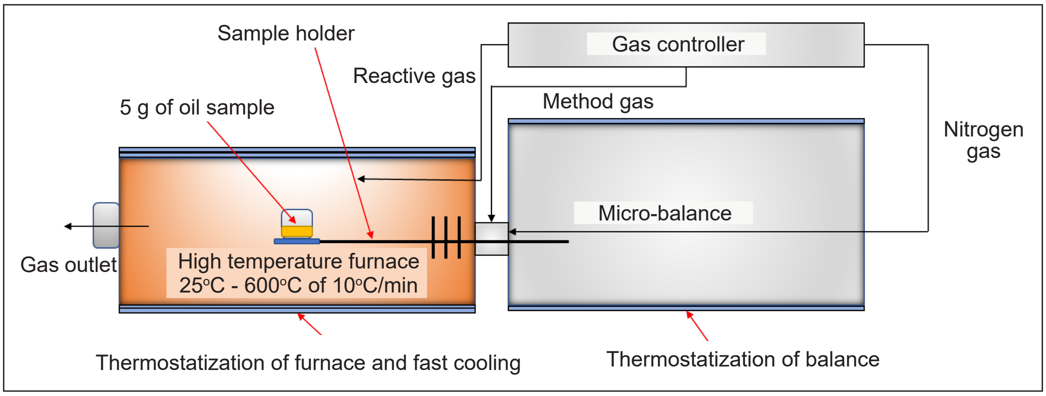


Figure 8. Thermogravimetric analysis and differential scanning calorimetry test of oil

Next, the paper was cut into confetti with dimensions 2 mm before the moisture content was determined using the oven method. In total, 0.1 g of the sample was weighed and mixed with 22.5 ml of distilled water in a beaker. Next, the solution was left for 30 minutes before fragmentised in a wet kitchen blender for up to 15 minutes. Next, 22.5 ml Copper (II) ethylenediamine (CED) solution was added and stirred for 2 hours. The mixture was added to the Cannon-Ubbelohde capillary tube viscometer. The viscometer was inserted into a constant water bath at 20°C. Once the tube's temperature was stabilised, the viscosity measurement was performed. The measurement was carried out for 4 times, whereby the average was used for the analysis. The calibration was performed based on the viscosity determination of the blank solution with a CED-to-water ratio of 50:50.

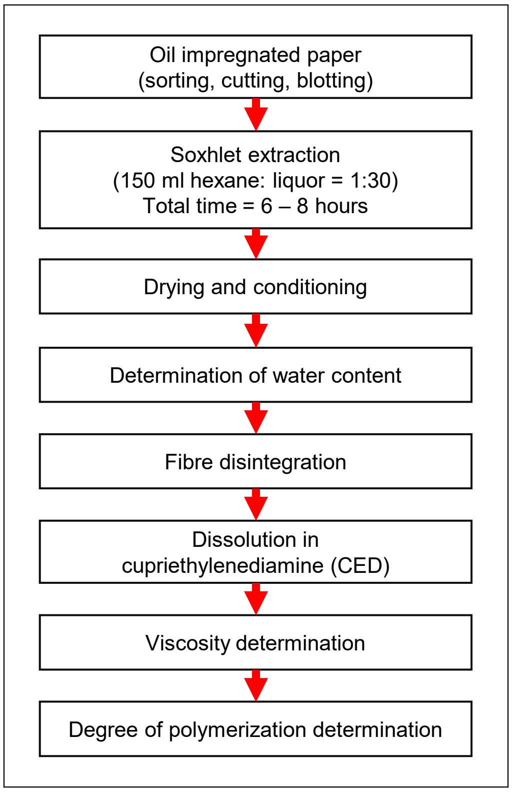


Figure 9. Measurement process of degree of polymerization

From the solution prepared, the concentration (c) was calculated based on Equation 2

$$c = \frac{100m\,(100 - \%MC)}{4500 + m(\%MC)} \qquad [2]$$

Where m is the mass of paper, g, and MC is the moisture content of the paper, %.

DP was calculated based on Mark Houwink constants where α and K were defined as 1 and 7.5 × 10^{-3}, respectively (Equation 3).

$$DP^{\alpha} = \frac{[\eta]}{K} \quad [3]$$

Where [η] is the intrinsic viscosity related to the specific viscosity, η_s and can be determined based on Equation 4.

$$\eta_s = \eta_{rel} - 1 = [\eta](10^{K[\eta]c}) \quad [4]$$

Where η_{rel} is the relative viscosity that can be defined based on Equation 5.

$$\eta_{rel} = \frac{\text{Kinematic viscosity of the solution}}{\text{Kinematic viscosity of CED}} \quad [5]$$

[η].c can be obtained from Table 1 in ASTM D4243 (2023). The intrinsic viscosity [η] can be determined using the c from Equation 2. DP can be estimated based on Equation 3.

RESULTS AND DISCUSSION

AC Breakdown Voltage of RBDPO and MO

The AC BDV of RBDPO is higher than MO at all moisture levels after 7 days of ageing, as shown in Figure 10. The decrement pattern of AC BDV for MO is steeper than RBDPO as the moisture increases. In the presence of high moisture, LMA and oxygen, the AC BDV of RBDPO decreases by 12%, while for MO, it decreases by 73%.

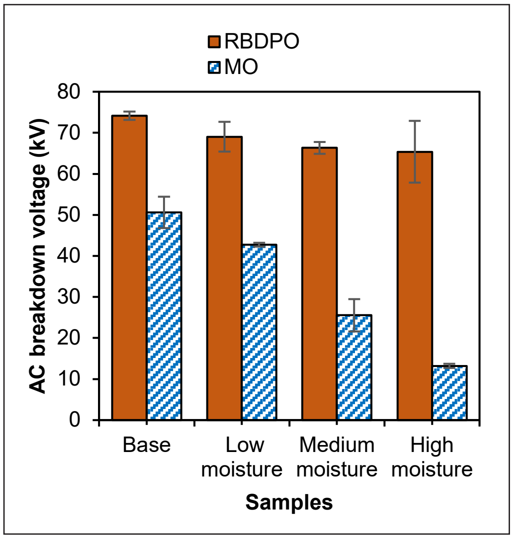


Figure 10. AC breakdown voltage of RBDPO and MO in the presence of moisture, LMA and oxygen

AC Breakdown Voltage of RBDPO and MO-Impregnated Paper

At all moisture levels, the AC BDV of RBDPO-impregnated paper is higher than MO-impregnated paper after 7 days of ageing, as seen in Figure 11. The AC BDV of RBDPO-impregnated paper slightly increases with the introduction of low moisture and decreases with the moisture increment. The same pattern is found for AC BDV of MO-impregnated paper. In the presence of high moisture, LMA and oxygen, the AC BDV of RBDPO and MO-impregnated paper slightly increased by 16.88% and 18.02% compared to the base.

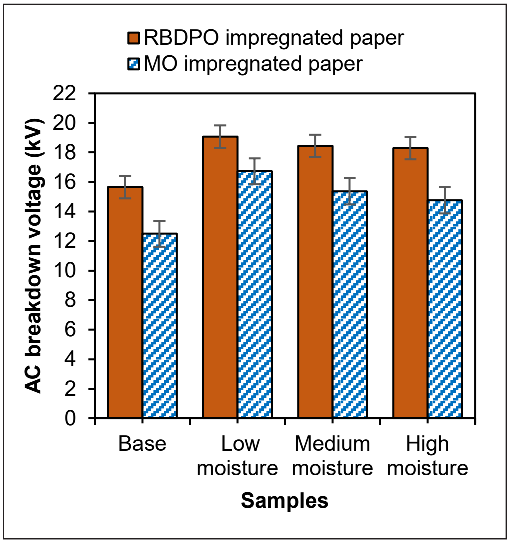


Figure 11. AC breakdown voltage of RBDPO and MO-impregnated paper in the presence of moisture, LMA and oxygen

Tensile Index of RBDPO and MO Impregnated Paper

The reduction pattern of TI is quite similar to DP at all moisture levels after 7 days of ageing, as shown in Figure 12. RBDPO-impregnated paper experiences a lower reduction of TI than MO-impregnated paper. Similar to DP, the TI of both RBDPO and MO-impregnated papers still suffer advanced degradation at low moisture. The lowest TI for RBDPO-impregnated paper is still higher than the 50% retention strength limit per IEEE standard C57.91-2011(IEEE Standards Association, 2012). With high moisture, the TI of MO-impregnated paper exceeds the limit with a percentage reduction of 59.54%. The ageing factor based on TI for RBDPO-impregnated paper in the presence of low, medium and high moistures is 1.41, 1.40 and 1.45. For MO-impregnated paper, the ageing factors are 1.64, 1.80 and 2.47, respectively.

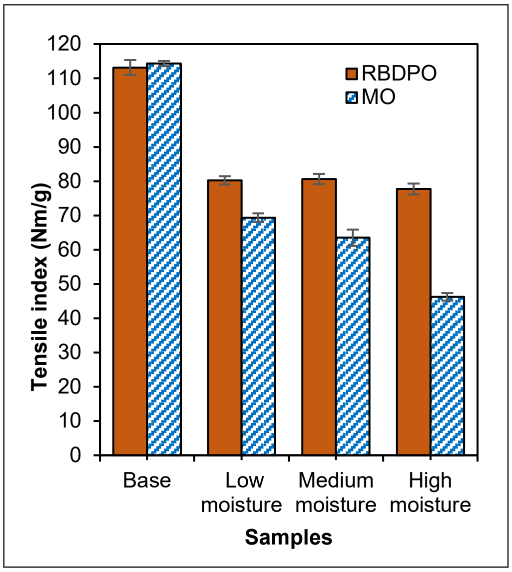


Figure 12. Tensile index of RBDPO and MO-impregnated papers in the presence of moisture, LMA and oxygen

Degree of Polymerization of RBDPO and MO-Impregnated Paper

The DP reduction of RBDPO-impregnated paper is lower than MO-impregnated paper at all moisture levels after 7 days of ageing, as seen in Figure 13. Even with the introduction of low moisture, both RBDPO and MO-impregnated papers still experience significant degradation, possibly due to the presence of LMA. The lowest DP for RBDPO-impregnated paper is 319 in the presence of high moisture. On the other hand, the DP for MO-impregnated paper decreases lower than 200, reaching the end of its life (Emsley et al., 2000.). The ageing factor based on DP for RBDPO-impregnated paper in the presence of low, medium and high moistures is 2.04, 2.07 and 2.96. For MO-impregnated paper, the ageing factors are 2.47, 4.44 and 4.57, respectively.

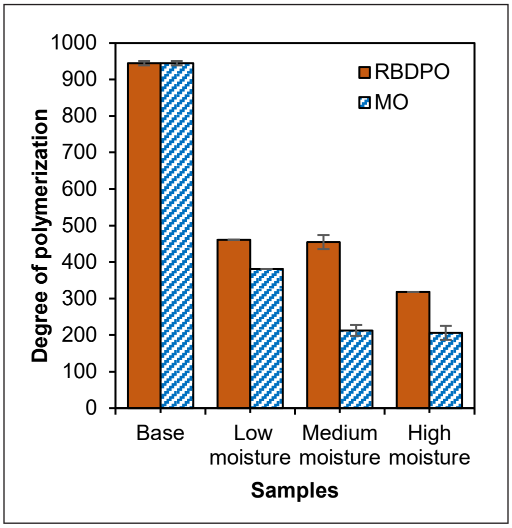


Figure 13. Degree of polymerization of RBDPO and MO-impregnated papers in the presence of moisture, LMA and oxygen

Thermogravimetric and Differential Scanning Calorimetry Analysis of RBDPO and MO

The onset temperature, or the temperature at which degradation begins, is useful for the oil stability (Raof et al., 2019). All RBDPOs are more resistant against degradation as compared to MO since the onset temperatures are high at all moisture levels after 7 days of ageing, as shown in Table 2 and Figure 14. The base RBDPO is stable up to 396°C, whereas base MO is only stable up to 296°C. MO exhibits a high weight loss of 72% in high moisture at 315.5 °C. The weight loss at the low-temperature range for MO is attributed to the evaporation of low molecular weight hydrocarbons and degradation of the base oil. According to Tripathi & Vinu (2015), the degradation of MO can occur at the temperature range between 150°C and 350°C. For example, the paraffinic chain in the MO molecules can decompose into ethane (C_2H_6), ethylene (C_2H_4), methane (CH_4), hydrogen (H_2) and graphite carbon. At a similar moisture level, the weight loss for RBDPO is only 61% at 431.5°C. RBDPO contains high triglyceride molecules such as palmitic and oleic acids, contributing to its higher thermal stability than MO. The increment of the hydrocarbon chain length and branching in the RBDPO's molecule decreases the weight loss and decomposes much slower (Raof et al.,

Table 2
The decomposition temperatures of the RBDPO and MO

Sample	Conditions	Onset temperature (°C)	Peak temperature (°C)	Weight loss (%)
MO	Base	295.6	330.6	57.6
	Low	293.4	329.8	56.1
	Medium	283.3	330.2	62.4
	High	238.5	315.5	72.1
RBDPO	Base	395.7	431.0	59.3
	Low	393.3	429.0	58.4
	Medium	394.4	431.7	61.0
	High	394.6	431.5	61.4

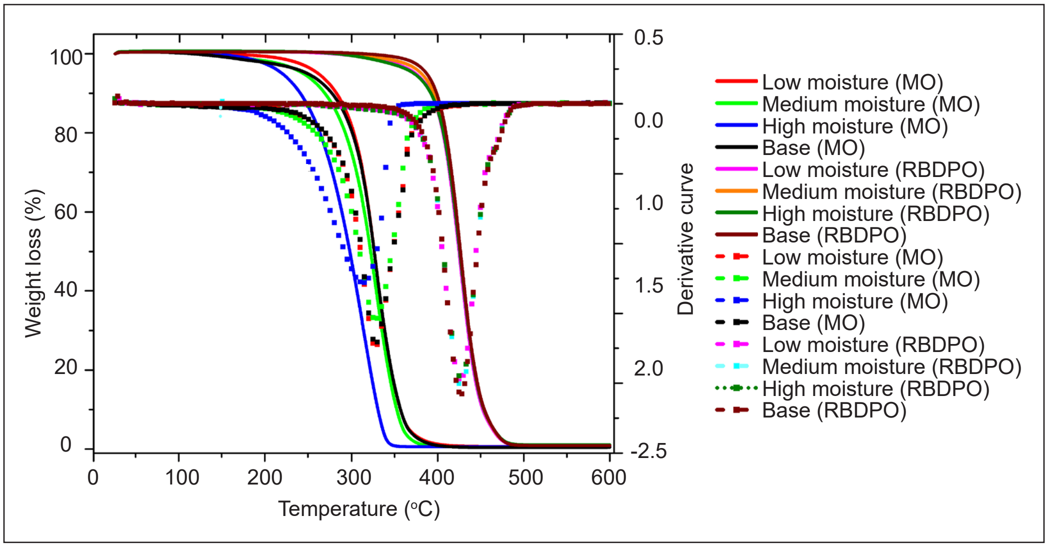


Figure 14. Thermogravimetric analysis and differential scanning calorimetry of the RBDPO and MO for weight loss and derivative curves in the presence of moisture, LMA and oxygen

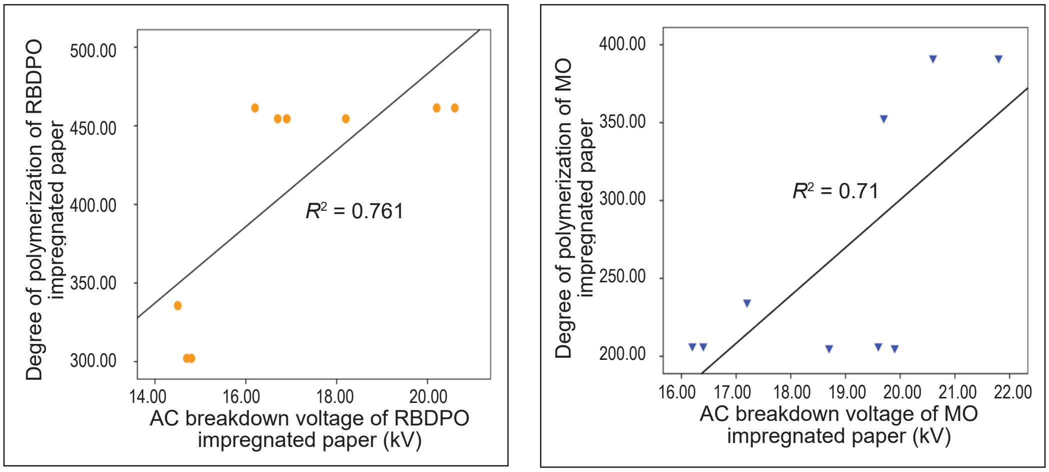
2019). The relatively low decomposition temperature for RBDPO and MO with high moisture content can be attributed to the high volatility of water at a low temperature.

Correlation Between Degree of Polymerization and AC Breakdown Voltage of RBDPO and MO Impregnated Paper

The correlation between DP and AC BDV of RBDPO and MO-impregnated paper at all moisture levels after 7 days of ageing can be seen in Figure 15. The result shows that the correlation coefficient, R^2, for RBDPO and MO-impregnated papers are 0.761 and 0.71, respectively. The correlation coefficient number, which ranges from -1 to 1, describes the strength and direction of the linear link between two quantitative variables. The R^2 from the linear relationship near 1 indicates a strong relationship whereby the range is between 0.7 and 0.99 (Ghoneim, 2021). Meanwhile, positive notation indicates the positive direction, showing that the 2 variables move in the same direction and vice versa. Moreover, it is found that there is a relationship between DP and AC BDV of RBDPO and MO-impregnated papers, which indicates that the reduction of mechanical strength leads to the reduction of electrical strength.

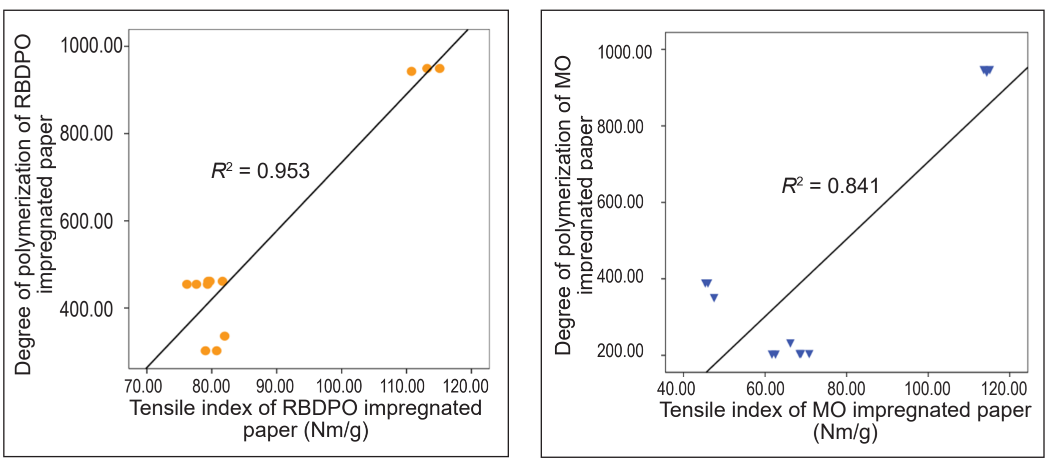
Correlation Between Degree of Polymerization and Tensile Index

The correlation between DP and TI after being subjected to ageing at all moisture levels after 7 days of ageing can be seen in Figure 16. The result shows that the correlation coefficient, R^2, for RBDPO and MO-impregnated papers are 0.953 and 0.841, respectively. The positive notation between the decreases and increases of DP and TI can be observed



(a) (b)

Figure 15. Positive correlation between DP and AC BDV of: (a) RBDPO; and (b) MO-impregnated papers



(a) (b)

Figure 16. Positive correlation between DP and TI of: (a) RBDPO; and (b) MO-impregnated papers

through the linear regression. The results are in line with the study by (Arroyo et al., 2017), which suggests that the paper strength directly depends on the depolymerization of the cellulose as well as on factors of the inter-fibre bond strength among the cellulose fibres, individual fibre strength and the hierarchical structure of the paper.

CONCLUSION

This work examines the effects of initial ageing conditions in the presence of LMA, oxygen, and various degrees of moisture content of the paper at 140°C for 7 days are examined. The AC BDV for RBDPO experiences lower reduction than MO with the moisture increment. The reduction of AC BDV of RBDPO-impregnated paper is still lower than MO-impregnated papers as the moisture level increases from low to high. The reduction trends of both DP and TI of RBDPO-impregnated papers show that the ageing performance is slightly better than MO-impregnated paper, even at high moisture content. RBDPO is more stable and resistant against ageing than the MO with high onset initial temperature. Overall, even with the presence of LMA, oxygen and high moisture, RBDPO is able to perform better than MO based on the condition under study.

ACKNOWLEDGEMENT

The authors express their gratitude to the Ministry of Higher Education, Malaysia, for the financing provided under the FRGS programme under the designation of FRGS/1/2019/TK07/UPM/02/3 (03-01-19-2071FR), Universiti Teknologi MARA (UiTM), Malaysia, and Majlis Amanah Raya (MARA), Malaysia. Special thanks to Malaysia Transformer Manufacturing Sdn. Bhd., Malaysia, and Hyrax Oil Sdn. Bhd., Malaysia for the technical support.

REFERENCES

Abdelmalik, A. A. (2015). Analysis of thermally aged insulation paper in a natural ester-based dielectric fluid. *IEEE Transactions on Dielectrics and Electrical Insulation*, *22*(5), 2408-2414. https://doi.org/10.1109/TDEI.2014.004824

Arroyo, O. H., Jalbert, J., Fofana, I., & Ryadi, M. (2017). Temperature dependence of methanol and the tensile strength of insulation paper: Kinetics of the changes of mechanical properties during ageing. *Cellulose*, *24*(2), 1031-1039. https://doi.org/10.1007/s10570-016-1123-7

ASTM D1816-12. (2019). *Standard test method for dielectric breakdown voltage of insulating liquids using VDE electrodes*. ASTM International. https://www.astm.org/Standards/D1816.htm

ASTM D974. (2023). *Standard test method for acid and base number by color-indicator titration.* ASTM International. https://www.astm.org/d0974-22.html.

ASTM D6304. (2021). *Standard test method for determination of water in petroleum products, lubricating oils, and additives by coulometric karl fischer titration*. ASTM International. https://www.astm.org/d6304-20.html

ASTM D4243. (2023). *Standard test method for measurement of average viscometric degree of polymerization of new and aged electrical papers and boards.* ASTM International. https://www.astm.org/d4243-16.html

Azis, N., & Wang, Z. D. (2011, August 22-26). *Acid generation study of natural ester*. [Paper presentation]. XVII International Symposium on High Voltage Engineering, Hannover, Germany.

Azis, N., Jasni, J., Ab Kadir, M. Z. A., & Mohtar, M. N. (2014). Suitability of palm based oil as dielectric insulating fluid in transformers. *Journal of Electrical Engineering and Technology*, *9*(2), 662-669. https://doi.org/10.5370/JEET.2014.9.2.662

Carcedo, J., Fernández, I., Ortiz, A., Delgado, F., Renedo, C. J., & Pesquera, C. (2015). Aging assessment of dielectric vegetable oils. *IEEE Electrical Insulation Magazine*, *31*(6), 13-21. https://doi.org/10.1109/MEI.2015.7303258

Ciuriuc, A., Notingher, P. V., Jovalekic, M., & Tenbohlen, S. (2014, May 22-24). *Experimental study on vegetable and mineral transformer oils properties*. [Paper presentation]. International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), Bran, Romania. https://doi.org/10.1109/OPTIM.2014.6850907

Coulibaly, M. L., Perrier, C., Beroual, A., & Marugan, M. (2012, September 23-27). T*hermal aging of paper and pressboard in mineral and ester oils under air and nitrogen atmospheres.* [Paper presentation]. IEEE International Conference on Condition Monitoring and Diagnosis, Bali, Indonesia. https://doi.org/10.1109/CMD.2012.6416449

Emsley, A. M., Xiao, X., Heywood, R. J., & Aii, M. (2000). Degradation of cellulosic insulation in power transformers. Part 3: Effects of oxygen and water on ageing in oil. *IEE Proceedings-Science, Measurement and Technology, 147*(3), 115-119. https://doi.org/10.1049/ip-smt:20000021

Ghoneim, S. S. M. (2021). The degree of polymerization in a prediction model of insulating paper and the remaining life of power transformers. *Energies*, *14*(3), Article 670. https://doi.org/10.3390/en14030670

Gomna, A., N'Tsoukpoe, K. E., Le Pierrès, N., & Coulibaly, Y. (2019). Review of vegetable oils behaviour at high temperature for solar plants: Stability, properties and current applications. *Solar Energy Materials and Solar Cells*, *200*, Article 109956. https://doi.org/10.1016/j.solmat.2019.109956

Ismail, N., Arief, Y. Z., Adzis, Z., Azli, S. A., Jamil, A. A. A., Mohd, N. K., Huei, L. W., & Kian, Y. S. (2013). Effect of water on electrical properties of refined, bleached, and deodorized palm oil (RBDPO) as electrical insulating material. *Jurnal Teknologi (Sciences and Engineering)*, *64*(4), 97-101. https://doi.org/10.11113/jt.v64.2108

Kiasatina, Kamarol, M., Zulhilmey, M., & Arief, Y. A. (2011, June 21-22). *Breakdown characteristics of RBDPO and soybean oil mixture for transformer application.* [Paper presentation]. International Conference on Electrical, Control and Computer Engineering (InECCE), Kuantan, Malaysia. https://doi.org/10.1109/INECCE.2011.5953879

Kouassi, K. D., Fofana, I., Cissé, L., Hadjadj, Y., Yapi, K. M. L., & Diby, K. A. (2018). Impact of low molecular weight acids on oil impregnated paper insulation degradation. *Energies*, *11*(6), Article 1465. https://doi.org/10.3390/en11061465

Maharana, M., Baruah, N., Nayak, S. K., Meher, N., & Iyer, P. K. (2019). Condition assessment of aged ester-based nanofluid through physicochemical and spectroscopic measurement. *IEEE Transactions on Instrumentation and Measurement, 68*(12), 4853-4863. https://doi.org/10.1109/TIM.2019.2900883

Maharana, M., Nayak, S. K., & Sahoo, N. (2018). Karanji oil as a potential dielectrics liquid for transformer. *IEEE Transactions on Dielectrics and Electrical Insulation*, *25*(5), 1871-1879. https://doi.org/10.1109/TDEI.2018.007230

Makmud, M. Z.H., Illias, H. A., Chee, C. Y., & Sarjadi, M. S. (2018). Influence of conductive and semi-conductive nanoparticles on the dielectric response of natural ester-based nanofluid insulation. *Energies*, *11*(2), Article 333. https://doi.org/10.3390/en11020333

Makmud, M. Z. H., Illias, H. A., Chee, C. Y., & Dabbak, S. Z. A. (2019). Partial discharge in nanofluid insulation material with conductive and semiconductive nanoparticles. *Materials, 12*(5), Article 816. https://doi.org/10.3390/MA12050816

Martin, D., Wang, Z. D., Darwin, A. W., & James, I. (2006, October 15-18). *A comparative study of the chemical stability of esters for use in large power transformers.* [Paper presentation]. IEEE Conference on Electrical Insulation and Dielectric Phenomena, Kansas City, USA. https://doi.org/10.1109/CEIDP.2006.311977

Matharage, S. Y., Liu, Q., & Wang, Z. D. (2016). Aging assessment of kraft paper insulation through methanol in oil measurement. *IEEE Transactions on Dielectrics and Electrical Insulation*, *23*(3), 1589-1896. https://doi.org/10.1109/TDEI.2016.005564

Mohamad, N. A., Azis, N., Jasni, J., Kadir, M. Z. A. A., Yunus, R., Ishak, M. T., & Yaakub, Z. (2016). Investigation on the dielectric, physical and chemical properties of palm oil and coconut oil under open thermal ageing condition. *Journal of Electrical Engineering and Technology*, *11*(3), 690-698. https://doi.org/10.5370/JEET.2016.11.3.690

Mohamad, N. A., Azis, N., Jasni, J., Kadir, Z. A. A., Yunus, R., Ishak, M. T., & Yaakub, Z. (2015). Analysis on the degradation of insulation paper in palm oil and coconut oil under high temperature ageing. *Jurnal Teknologi, 72*(1), 1-6.

Munajad, A., Subroto, C., & Suwarno. (2017). Study on the effects of thermal aging on insulating paper for high voltage transformer composite with natural ester from palm oil using fourier transform infrared spectroscopy (ftir) and energy dispersive x-ray spectroscopy (EDS). *Energies*, *10*(11), Article 1857. https://doi.org/10.3390/en10111857

N'cho, J. S., Fofana, I., Hadjadj, Y., & Beroual, A. (2016). Review of physicochemical-based diagnostic techniques for assessing insulation condition in aged transformers. *Energies, 9*(5), Article 367. https://doi.org/10.3390/en9050367

Suwarno, & Pasaribu, R. (2017, September 11-15). *Effects of Thermal Aging on Paper Characteristics in Paper-Mineral Oil composite Insulation*. International Symposium on Electrical Insulating Materials (ISEIM), Toyohashi, Japan. https://doi.org/10.23919/ISEIM.2017.8166587

IEEE Standars Associaltion. (2012). *IEEE guide for loading mineraloil-immersed transformers and step-voltage regulators*. IEEE Standars Associaltion. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6166928

Raj, R. A., Samikannu, R., Yahya Began, A., & Mosalaosi, M. (2020). Comparison of ageing characteristics of superior insulating fluids with mineral oil for power transformer application. *IEEE Access*, *8*, 141111-141122. https://doi.org/10.1109/ACCESS.2020.3012988

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*, Article 105852. https://doi.org/10.1016/j.triboint.2019.105852

Rapp, K. J., McShane, C. P., & Luksich, J. (2005, June 26- July 1). *Interaction mechanisms of natural ester dielectric fluid and kraft paper*. [Paper presntation]. IEEE International Conference on Dielectric Liquids (ICDL), Coimbra, Portugal. https://doi.org/10.1109/icdl.2005.1490108

Raymon, A., Pakianathan, P., E. Rajamani, M. P., & Karthik, R. (2013). Enhancing the critical characteristics of natural esters with antioxidants for power transformer applications. *IEEE Transactions on Dielectrics and Electrical Insulation*, *20*(3), 899-912. https://doi.org/10.1109/TDEI.2013.6518959

RSPO. (2015). *Impact Update 2015*. Roundtable on Sustainable Palm Oil. https://www.helikonia.co.uk/wp-content/uploads/2020/12/FA-RSPO-Impact-Update-2015_SINGLE.pdf

Sinan, S. S., Shawaludin, S. N., Jasni, J., Azis, N., Ab Kadir, M. Z. A., & Mohtar, M. N. (2014, May 23-23). *Investigation on the AC breakdown voltage of RBDPO Olein.* [Paper presentation]. IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA), Kuala Lumpur, Malaysia. https://doi.org/10.1109/ISGT-Asia.2014.6873888

Suleiman, A. A., Muhamad, N. A., Bashir, N., Murad, N. S., Arief, Y. Z., & Phung, B. T. (2014). Effect of moisture on breakdown voltage and structure of palm based insulation oils. *IEEE Transactions on Dielectrics and Electrical Insulation*, *21*(5), 2119-2126. https://doi.org/10.1109/TDEI.2014.004431

Suryani, S., Sariani, S., Earnestly, F., Marganof, M., Rahmawati, R., Sevindrajuta, S., Indra Mahlia, T. M., & Fudholi, A. (2020). A comparative study of virgin coconut oil, coconut oil and palm oil in terms of their active ingredients. *Processes*, *8*(4), Article 403. https://doi.org/10.3390/PR8040402

Tripathi, A. K., & Vinu, R. (2015). Characterization of thermal stability of synthetic and semi-synthetic engine oils. *Lubricants*, *3*(1), 54-79. https://doi.org/10.3390/lubricants3010054

Vihacencu, M. Ș., Ciuriuc, A., & Dumitran, L. M. (2013). Experimental study of electrical properties of mineral and vegetable transformer oils. *UPB Scientific Bulletin, Series C: Electrical Engineering*, *75*(3), 171-182.

Wilhelm, H. M., Tulio, L., Jasinski, R., & Almeida, G. (2011). Aging markers for in-service natural ester-based insulating fluids. *IEEE Transactions on Dielectrics and Electrical Insulation*, *18*(3), 714-719. https://doi.org/10.1109/TDEI.2011.5931057