

Article

Experimental Study of the Electrical and Physiochemical Properties of Different Types of Crude Palm Oils as Dielectric Insulating Fluids in Transformers

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Abstract: This paper gives information on the electrical and physiochemical characteristics of six different types of palm oil compared with traditional mineral oil. We found that natural processed crude palm oil (PO-C) had a higher resistance to AC breakdown voltage than other types of palm oil, including traditional mineral oil. The results of the positive lightning impulse voltage test for PO-C were still the highest compared to other types of palm oil, including traditional mineral oil, at 58.26%. The summarised dissipation factors of all tested crude palm oils were significantly higher than those of mineral oils, which will make the palm oil less insulating, especially in PO-A palm oil (36.197%), where the values were higher than those of other oils, while mineral oil has a slightly increased dispersion factor. For relative permittivity, all palm oils were compared, and it was found that PO-C had a lower relative permittivity than the other oils. In terms of physical and chemical properties, in the moisture content test on all oils, PO-C had the percentile with the highest moisture content decrease of 58.74%. In the case of testing the surface tension value, it was found that traditional mineral oil had the highest value (48.46 m/Nm) when compared to palm oil. On the other hand, the acidity in traditional mineral oil is the lowest (0.03 mg KOH/g) compared to all palm oils. Results from studies demonstrate the possibility of using natural processed crude palm oil, or PO-C, as a replacement for traditional mineral oil. This is consistent with the results of electrical properties that show PO-C is higher than other types of palm oil and includes traditional mineral oil.

Keywords: liquid insulation; dielectric strength; dielectric loss; breakdown voltage and Karl Fischer titration method

1. Introduction

Transformers are devices that are very important in power transmission systems. Power transformers consist of conductors, steel cores, and insulators. The internal insulation of a power transformer consists of solid and liquid insulators. Solid insulators such as paper, board, and pressboard act as electrical insulators and support mechanical forces. As for the liquid insulator, it is used as the main insulator, acts as an electrical insulator, and serves to cool down the transformer. Due to their superior electrical characteristics and accessibility, mineral oils with a petroleum basis have been employed as dielectric and insulating fluids in transformers for decades [1,2]. The fundamental composition of insulating oils has seen few alterations since the inception of transformer oil in 1892, as developed by Thompson [3]. Nevertheless, significant advancements have been made in

the cleansing and production procedures of oils, as well as in the use of additives. There are two primary categories of transformer oils derived from mineral oil: paraffinic-based oils and naphthenic-based oils [4]. However, there are certain restrictions still in place, and mineral oil has a number of problems, including low flash and fire points and a low ignition point of roughly 150 °C. Moreover, when the moisture content is just 10–25 ppm, the voltage resistance is significantly decreased [5,6]. In addition, mineral oil has limited biodegradability and may contaminate soils and rivers in the event of large spills [7]. Additionally, mineral oil is a non-renewable resource [8]. Recently, the electrical sector has been more interested in environmental issues, which has prompted substantial attempts to look for alternatives to mineral oil. Nowadays, there is a focus on living things, and it is more environmentally friendly; therefore, various types of liquid insulators have been improved with the objective of having good electrical properties and being environmentally friendly. Natural ester oils are made from renewable soybean crops and have similarities to palm oil, which is obtained from the fruits of palm trees. Both ester oils and palm oils have characteristics that make them extremely biodegradable, renewable, and ecologically benign. The surface breakdown qualities of the substance are exceptional, and it exhibits a high flash point when compared to mineral oils. On the other hand, silicon oil has shown exceptional efficacy in the realm of catastrophe avoidance [9]. However, ester oil and silicon oil's prices are several times higher than palm oil. Therefore, palm oil is another attractive option, as it is relatively cheap and easily available, especially in Thailand.

Palm oil is a type of liquid insulation that meets these criteria. Palm oil, which was later developed for transformer applications, has been discovered as a potential insulating fluid. Palm oils are natural esters comprised of both saturated and unsaturated glycerol tribasic esters. Palm oil has numerous advantages, including outstanding biodegradability, excellent electrical properties, high fire resistance, and abundant resources. Palm oil, on the other hand, is an ester [10]. Palm oil, as a member of the natural ester group, shares many properties with other kinds of vegetable oils, including high flash and fire points, biodegradability, and environmental friendliness [11,12]. The electrical and physiochemical characteristics of new palm oil are comparable to varieties of natural esters and mineral oil, according to previous investigations [13,14]. Most of these characteristics are equivalent. Compared to other kinds of vegetable oils that are being aged at temperatures between 85 and 150 °C while being kept within acceptable ranges as per guidelines [15,16], the high temperature is ageing right now. The performance of palm oil needs further research since it has not been thoroughly established.

Therefore, natural palm oil has many strengths and shows interest in being used as a substitute for transformer oil. Therefore, in order to promote the use of renewable energy more and reduce environmental pollution, the proportion of palm oil must be increased to replace transformer oil produced from fossil fuels, and it also takes time to digest because it decomposes in nature for a long time. This paper aims to test the feasibility of using natural palm oil (crude palm oil and crude palm kernel oil) as a substitute for traditional transformer oil.

2. Materials and Methods

2.1. Samples Preparation

Preparation of Liquid Samples

Palm oil is produced when fruits are removed from oil palm bunches for oil extraction, leaving only the fruit's stem and spikelet. Palm oil is a vegetable oil that uses raw materials, namely the fruit of the palm tree, a yellow-orange oil scientifically known as *Elaeis guineensis*, which contains 45–55% oil [1,17]. Palm oil is obtained from two parts of the palm fruit: the mesocarp, the oil called palm oil, and the kernel, called palm kernel oil, as shown in Figure 1. Empty fruit bunches may contain as much as 60% moisture due to the combining of steam from the sterilising process of oil extraction and continuing biological development [18]. Palm oil obtained from the production process has a very high moisture

content. Therefore, before using palm oil for use or testing as a liquid insulator in electrical equipment, the moisture content in palm oil must be reduced first.



Figure 1. Products from the oil palm tree are: (a) fresh fruit bunches; (b) palm fruit.

Six palm oil products were investigated in this study, as shown in Table 1. All samples are obtained from readily available products in the palm oil industry of Thailand. Moreover, all types of natural palm oil were tested in comparison with conventional transformer oil. Naphthenic mineral oil from the APAR Company in India (POWEROIL TO 20 X) was used for the experimentation [19]. Preparation of palm oil samples began with adding palm oil samples to prepared beakers and vacuum drying with an oven heated to 60 °C for 24 h at a pressure of -0.08 MPa (model: Han Yang Scientific, Republic of Korea). This process was performed to lower the content of dissolved water in the samples, thereby enhancing the level of uniformity, as shown in Figure 2 [20].

Table 1. Palm oil samples description.

Samples		Description
Natural Crude Palm Oil	PO-A	crude palm oil
	PO-B	refined palm oil
	PO-C	processed crude palm oil
Natural Crude Palm Kernel Oil	PO-D	crude palm kernel oil
	PO-E	refined palm kernel oil
	PO-F	processed crude palm kernel oil

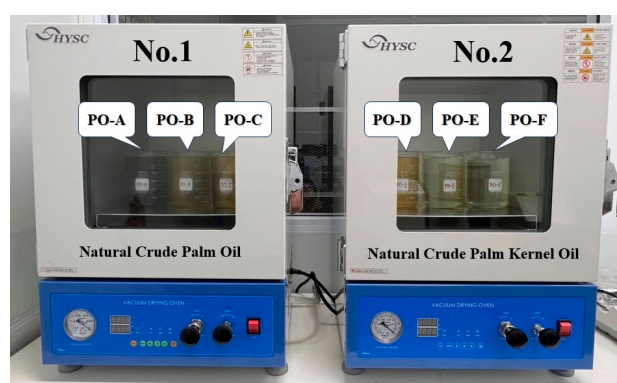


Figure 2. Preparation of liquid samples in vacuum drying ovens.

2.2. Measurement of Properties

2.2.1. AC Breakdown Voltage Measurement

AC breakdown voltage tests were performed on natural palm oil and conventional mineral oil. This was carried out through Huazheng Electric, a model HZJQ-1 transformer

oil dielectric strength tester and oil breakdown voltage testing tool with a rated 100 kV oil breakdown voltage analyser. The volume capacity of the test cell was 250 mL, and it was made up of sphere–sphere electrodes with a gap spacing of 2.5 mm and a diameter of 12.6 mm. As can be seen in Figure 3, the breakdown voltage test was carried out in accordance with the standards set out in IEC 60156 [21].

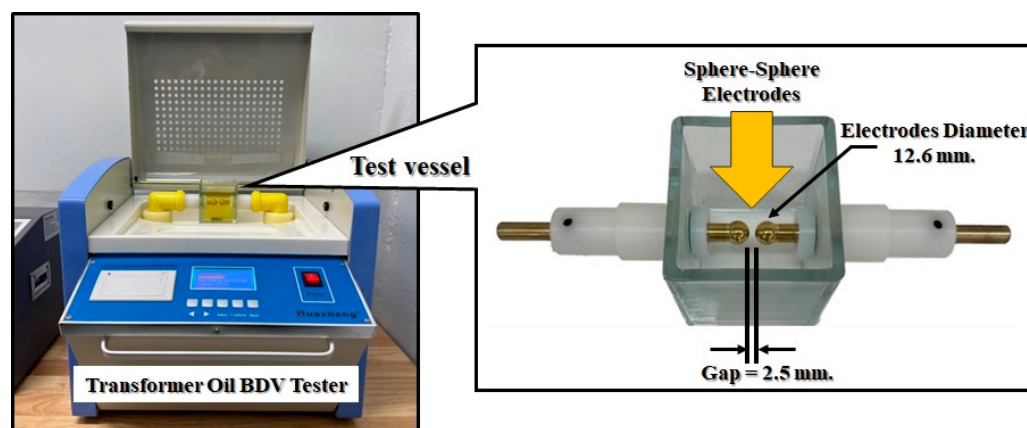


Figure 3. Measuring the AC breakdown strengths.

Initially, in the early stages of testing, the liquid insulation sample (natural palm oil or conventional mineral oil) is taken gradually. A total of 250 mL is added to the test vessel to minimise any air bubbles. Then, it is left for five minutes, and the voltage is adjusted in increments of 2 kV/s until a breakdown voltage is reached; after that, a 2 min interval is taken between each test until the breakdown voltage has been reached six times according to the standard. When finished, the AC breakdown value shown on the monitor is recorded. The new oil sample is replaced by the previous one, and a 5 min interval is taken after sample changes. Processes will be looped until the test is completed.

2.2.2. Lightning Impulse Breakdown Voltage Test

The lightning impulse breakdown strengths of natural palm oil and conventional mineral oil were examined using a test set model CJDY: 400 kV/40 kJ Impulse Voltage Generator from Jiangsu Shenghua Electric Co., Ltd., Yangzhou, China, at the High Voltage Research Laboratory, RMUTL. Figure 4 depicts an analogous circuit that may be used for testing as well as circuit preparation when attempting to measure the lightning impulse breakdown strengths of oil in accordance with IEC 60897 [22]. The high-voltage electrode in the experiment was a tungsten needle with a tip radius of 40 μm , and the grounded electrode was a brass sphere with a diameter of 13 mm. The needle–sphere electrode configuration in the experiment was established with a gap separation of 15 mm. At first, liquid insulating samples were slowly poured into the test vessel until it reached a capacity of 210 mL. This was carried out to prevent any air from escaping. Then, a sample of natural palm oil and a conventional sample of mineral oil were each put in the test vessel, and after five minutes, the vessel was examined for the presence of air bubbles until all of the air bubbles had been depleted.

The impulse waveforms T1 and T2 have now been analysed and compared using predetermined standards. If the period of the wave is T1, then it must be between 0.84 and 1.56 microseconds, and if the period of the wave tail is T2, then it must be between 40 and 60 μs . According to the requirements, the oil may be evaluated with the impulse voltage set at U_b (50%). If the oil did not break down at first, the impulse voltage was raised in 5 kV increments until it did. The subsequent voltage meter reading was recorded as a breakdown of a lightning impulse. As soon as the failure occurs, the old oil sample should be replaced with a fresh one for testing. Six tests were performed, with a 5 min break in between each one. When everything was finished, the mean values were recorded.

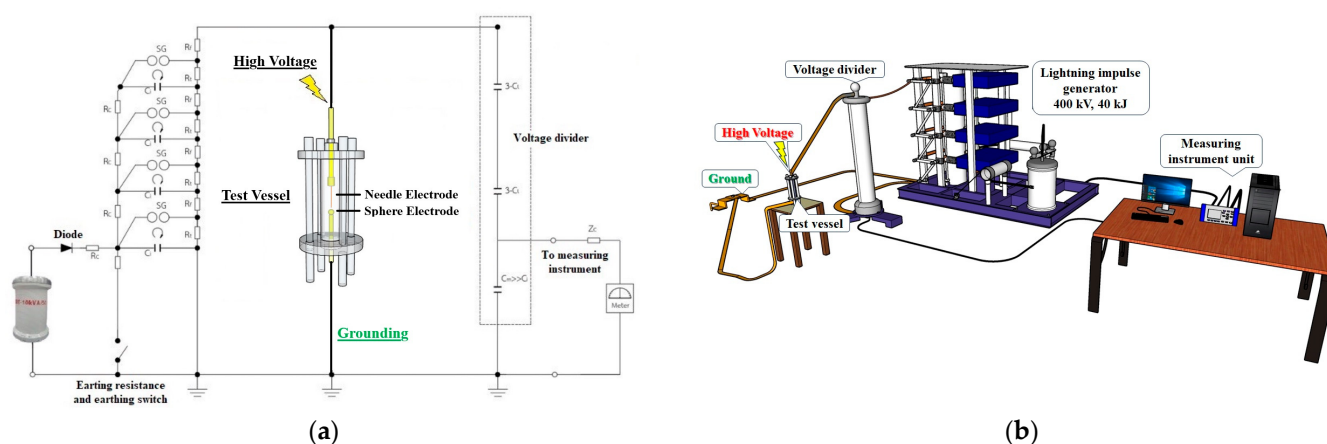


Figure 4. Test circuits for measuring lightning impulse breakdown voltage strengths: (a) equivalent circuit for measuring lightning impulse breakdown strengths; (b) test circuit preparation.

2.2.3. Dielectric Dissipation Factor (Tan Delta), Relative Permittivity and Resistivity

The dielectric characteristics of oil samples were assessed by using a Huazheng model HZJD-2 insulating oil dielectric loss and resistivity tester, as shown in Figure 5, in accordance with the guidelines specified in IEC 60247 [23]. The test cell used a three-electrode configuration in accordance with the national standard GB/T5654-2007 [24], including an electrode separation distance of 2 mm. The experimental procedure included testing a sample of oil with a volume of 40 mL at a specified temperature of 90 °C, as per the frequency range outlined in the IEC 60247 standard [23]. The voltages used for measuring the dielectric dissipation factor, relative permittivity, and resistivity were 1000 V (alternating current) and 500 V (direct current), correspondingly.

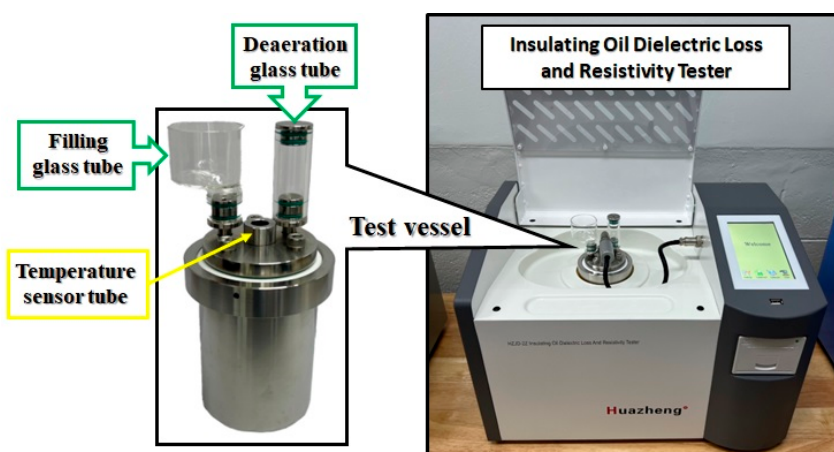


Figure 5. Measuring the dielectric dissipation factor, relative permittivity, and resistivity.

2.2.4. Moisture Content Measurement

Six palm oils and conventional mineral oils were both analysed for moisture content using the MITSUBISHI CA-310 moisture analyser model, as shown in Figure 6. According to ASTM D1533 [25], the oil's moisture content was measured using the Karl Fischer titration method. One millimetre of oil was taken out and put into titration vessels with CombiCoulomat fritless Karl Fischer reagent for each of the moisture measurements [26]. This paper was measured three times in total, and the analysis used the average value.

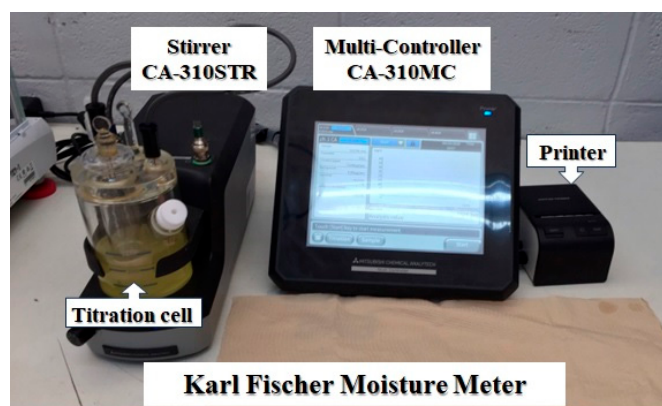


Figure 6. Measuring the moisture content.

2.2.5. Interfacial Tension Measurement

Liquid insulation surface tension is a result of the presence of intermolecular forces. The quantification of tensions shown by the liquid sample in relation to its physical and chemical characteristics is a crucial determinant of the quality of oil. This approach is commonly used due to its ability to sample and provide accurate results. In this study, an analysis was conducted to determine the interfacial tension of natural palm oil and conventional mineral oil. The Huazheng model HZZL-3 automated tension tester, as seen in Figure 7, was used for this purpose. The ASTM D971-20 [27] standard provides a comprehensive framework for evaluating various types of liquid surface tension and boundary surface tension.

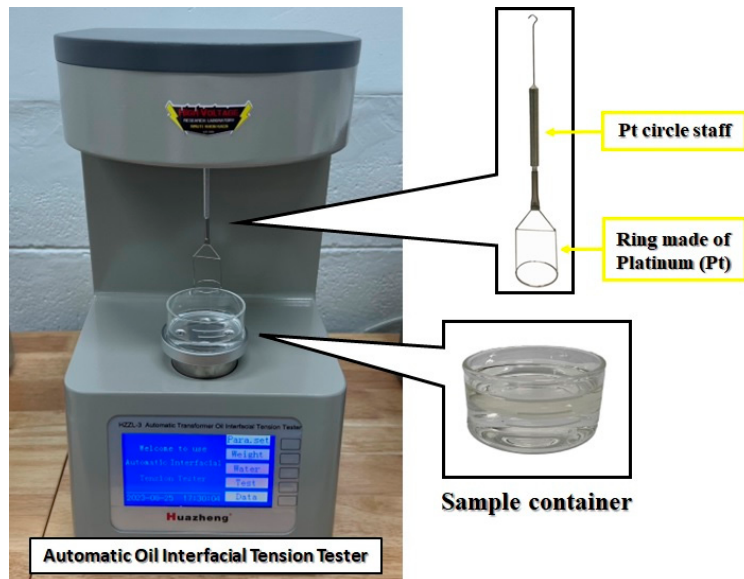


Figure 7. Measuring the interfacial tension.

2.2.6. Acid Values Measurement

In transformer oil, the acid value of the oil is a crucial indication of its suitability as a dielectric liquid. The oil may undergo an oxidation process, and the byproducts of other chemical processes may both contribute to the acidity of the oil. The dielectric property and other features of liquid insulation will suffer deterioration because of acid's reaction with water and solid impurities. In this paper, the amount of acid in both natural palm oil and regular transformer oil was measured using an automated oil acidity tester called the HuaZheng model HZCS-3, as shown in Figure 8. The measurement of acidity was performed in accordance with ASTM D974 [28].

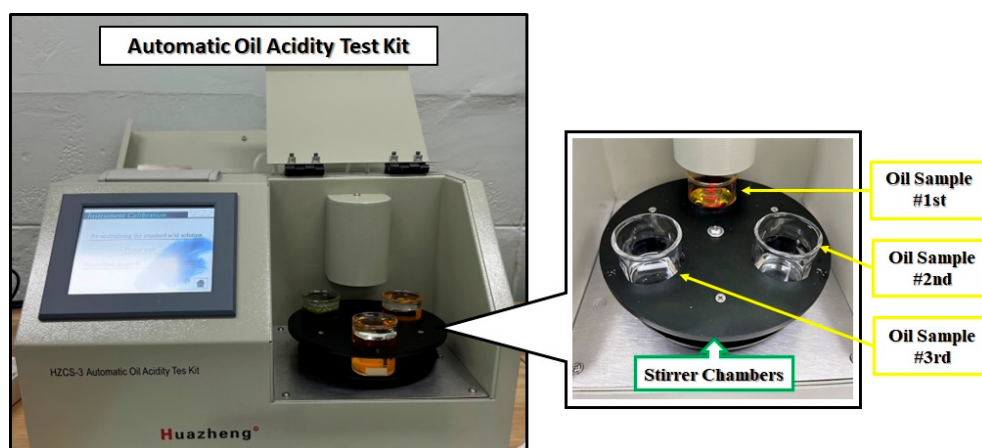


Figure 8. Measuring the acid values.

2.2.7. Ultraviolet-Visible (UV-VIS) Spectroscopy

The method of ultraviolet-visible (UV-VIS) spectroscopy has shown a significant association with a number of different physical and chemical parameters [29,30]. In addition to this, it has demonstrated a significant link with the dielectric losses that are associated with transformer oil [31]. Spectrophotometers that measure both the visible and ultraviolet spectra are known as UV-VIS spectrophotometers. These spectrophotometers are popular for conducting qualitative and quantitative analyses owing to their user-friendly operation and rapid sample analysis. A SPECORD PLUS Double Beam UV-vis spectrophotometer model called SPECORD[®] 200 PLUS, as shown in Figure 9, which is a combination monitor double beam spectrophotometer, was utilised for the analysis of natural palm oil and conventional mineral oil samples in this paper application.



Figure 9. Measuring the ultraviolet-visible spectroscopy.

2.2.8. Fourier Transformation Infrared (FTIR) Spectroscopy

Oil samples were analysed and characterised for their physical and chemical constituents using FTIR spectroscopy. Technology advancements have allowed for the characterisation of the physical and chemical properties of oils as dielectric insulating fluids in transformers [32,33]. To determine what molecules are present in a sample, FTIR spectroscopy uses the absorption or transmission of infrared light, which is used to differentiate between different molecules [34,35]. All of the oil samples in this paper (six types of natural palm oils and one conventional transformer oil) were analysed by FTIR using a Bruker Tensor 27 FTIR Spectrometer (Billerica, MA, USA) under the wave number range of 700 to 4000 cm^{-1} , as shown in Figure 10.



Figure 10. Measuring the Fourier transformation infrared spectroscopy.

3. Results and Discussion

3.1. Electrical Properties

3.1.1. AC Breakdown Voltage

The dielectric strength measures the electric field strength at which the insulation fails. The insulating material, contaminants, and electrode geometries all have a role, as does the electric field [36]. Mean breakdown values are often used to assess the quality of an insulating liquid. In this study, the breakdown voltages are fitted using the distributions. Figure 11 provides a comprehensive illustration of the average value at which PO-C exhibits the maximum breakdown voltage for dielectric strength. PO-B has the second-best AC breakdown voltage, whereas MO, PO-A, PO-D, PO-E, and PO-F show a drop in breakdown voltage in oil samples, correspondingly. In the meantime, the AC breakdown voltage of MO is found to be lower than that of PO-C, and this discovery is consistent with prior studies [37,38] in this regard. It is possible that contamination, specifically the oil sample's moisture [32] content or relative humidity, which both have an impact on the breakdown voltage, was the cause of this situation. It is possible for moisture to be acquired during the process of transferring the oil sample from the bottle to the test cell, which includes putting the oil sample in direct contact with the atmosphere. The oil samples have been proven to contain moisture because of the oil absorbing moisture from the atmosphere [37,39]. Moreover, the physicochemical features, impurities, and solid particles present in the liquid medium at the time of the test all contribute to the statistical quantity known as the breakdown strength of the medium [40,41]. In accordance with standard [42] of the IEC, this meets the prerequisite for the breakdown voltage of insulating fluids.

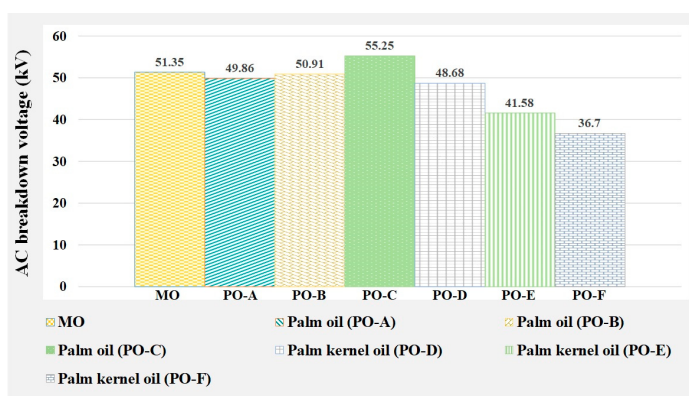


Figure 11. Comparison of the AC breakdown strengths between six palm oils and conventional mineral oils.

3.1.2. Lightning Impulse Breakdown Voltage

An investigation into the impulse breakdown strength is carried out in order to assess the impulse breakdown features of oil. When attempting to measure the quality of an insulating liquid, it is common practice to calculate the mean values of the breakdown [43]. On the other hand, transformers are constructed using the minimal amount of voltage that the insulation can sustain rather than the average level of voltage that it can resist. Figure 12 illustrates the average impulse breakdown voltages together with the lowest and maximum values for palm oil and traditional mineral oil respectively. Analysis of the data has shown that the impulse breakdown voltage in the results has shown that in palm oil samples PO-A, PO-B, PO-C, PO-E, and PO-F, the impulse breakdown voltage with positive polarity can be higher than in mineral oil, especially in palm oil PO-C, which has the highest breakdown strength, except for palm oil D, which is lower than mineral oil, as shown in Figure 12a. For the negative polarity of the impulse breakdown voltage, the results of the tests on all palm oil samples were still good when considering the tendency towards impulse-withstand values, especially palm oil PO-C, which has the highest value in the palm oil group. However, conventional mineral oil is stronger than all palm oil samples, as shown in Figure 12b. The polarity effect of the lightning impulse breakdown voltage is affected by the space charge as well as the distinct chemical structures of palm oil and mineral oil [44,45].

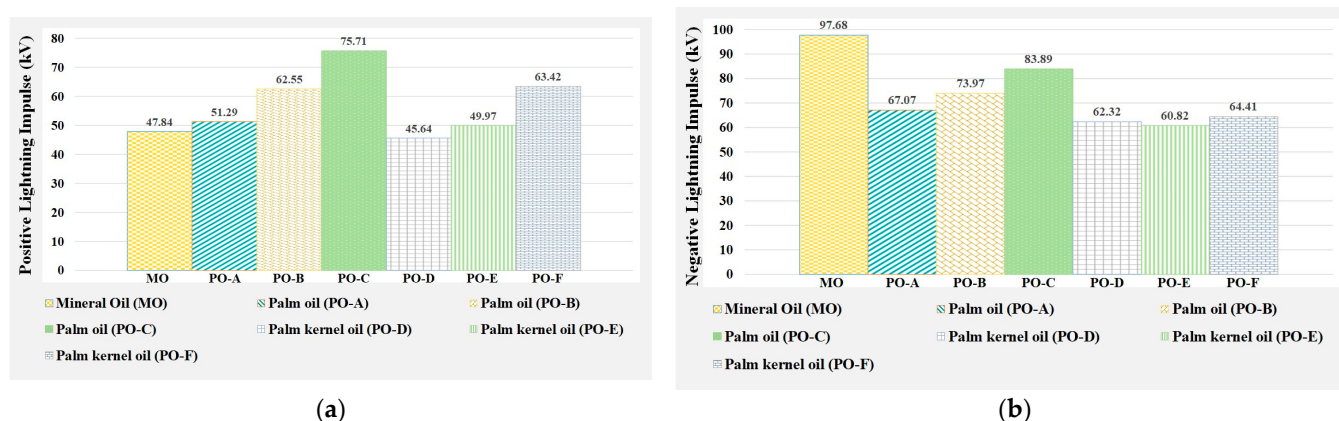


Figure 12. A comparison of the lightning impulse strengths between six palm oils and conventional mineral oils includes (a) positive lightning breakdown; and (b) negative lightning breakdown.

3.1.3. Dielectric Dissipation Factor, Relative Permittivity, and Resistivity

Table 2 shows the results of the dielectric dissipation factor ($\tan \delta$), relative permittivity (ϵ_r), and resistivity (ρ) of six palm oils and conventional mineral oils. All samples were measured at a temperature range of 90 °C. The values in Table 2 show that all palm oils have a higher $\tan \delta$ than conventional mineral oils, which agrees with the study carried out by Mehta et al. [46]. The chemical structure of vegetable oil is a little more polar than that of mineral oil, which is why palm oils have a higher diffusion factor value [47]. Based on the study, PO-C has a lower $\tan \delta$ value than PO-(A, B, D, E, and F), which can relate to PO-C having had the highest moisture content decrease of 58.74% in the effect of moisture content from drying under vacuum clearly having an impact on the moisture levels. In a similar way, the relative permittivity of six palm oils is higher than that of regular mineral oils, which may be because palm oils contain polar triglycerides. Typically, vegetable oil exhibits a greater degree of hygroscopicity, or water absorption, in comparison to mineral oil. This disparity may be attributed to the polar nature of water molecules, which may significantly impact the relative permittivity value of palm oils [37]. When the relative permittivity of all palm oils was compared, it was found that PO-C had a lower relative permittivity than the other oils. This could be because the fat levels in each oil were different.

Table 2. Results of measuring the dielectric dissipation factor, relative permittivity, and resistivity.

Liquid Samples Under Test Temperature of 90 °C		Tan δ (%)	ϵ_r	ρ (Ωm)
Mineral Oil	MO	0.242	1.599	6.22×10^9
	PO-A	36.197	2.266	5.26×10^8
Palm Oil	PO-B	10.829	2.232	1.43×10^9
	PO-C	3.074	1.966	7.01×10^9
	PO-D	9.116	2.224	2.31×10^9
Palm Kernel Oil	PO-E	5.593	2.081	5.11×10^9
	PO-F	3.470	2.167	6.63×10^9

Furthermore, the resistivity of insulating oils has significant importance as an electrical parameter, particularly in the context of their use in transformers. The material has a very high resistance, suggesting a limited presence of free ions, particles capable of generating ions, and a low concentration of conductive impurities. The resistivity of oil has a negative correlation with temperature, wherein an increase in temperature leads to a reduction in resistivity. The resistivity result of all oil samples in this study, PO-C, has a resistivity of $7.01 \times 10^9 \Omega\text{m}$ higher than all oil samples, which includes conventional mineral oil. Moreover, the oils with the highest resistivity will normally have the highest AC breakdown voltage. As mentioned in Figure 11, the higher breakdown voltage of palm oil (PO-C) is comparable to all oil samples in this study.

3.2. Physiochemical Properties

3.2.1. Moisture Content

In all the oil samples, the effect of moisture content from drying under vacuum clearly had an impact on the moisture levels [48]. The results of the testing of moisture content and a comparison of the average value of the moisture content between six palm oils and conventional mineral oils, including before and after drying under vacuum, are shown in Figure 13. According to the results of the moisture content test on all oils, palm oil PO-C had the highest moisture content decrease of 58.74%, mineral oil MO came in second with a decrease of 51.26%, palm oil PO-F came in third with a decrease of 43.35%, palm oil PO-A came in at 38.73%, palm oil PO-E came in at 34.85%, palm oil PO-D came in at 30.84%, and palm oil PO-B came in at 6.48%.

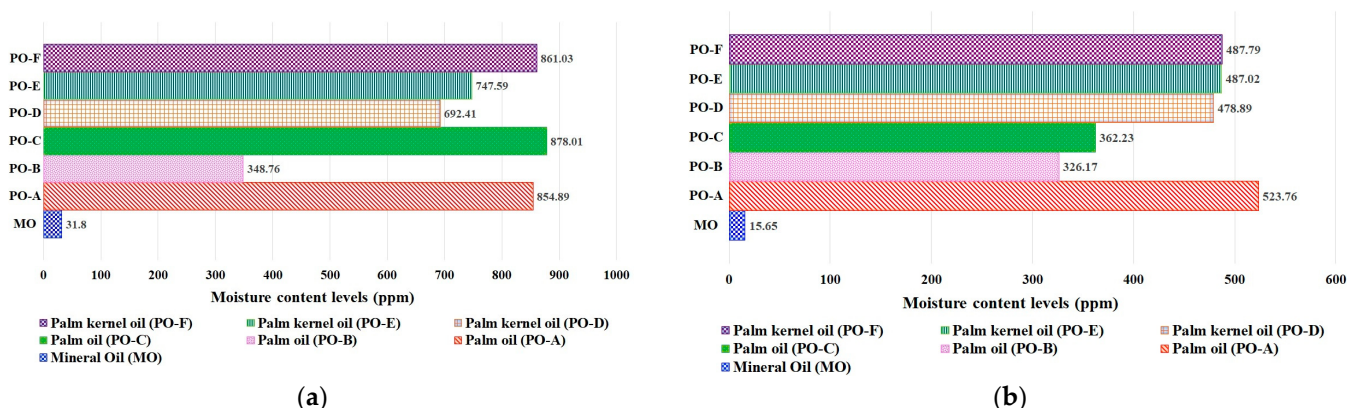


Figure 13. A comparison of the average value of the moisture content between six palm oils and conventional mineral oils includes (a) before drying under vacuum; and (b) after drying under vacuum.

At the same temperature under the testing conditions of this paper, the solubility of palm oil and mineral oil is vastly different owing to their different chemical compositions. Caixin Sun et al. [49] performed an experiment showing that at room temperature, vegetable

oil has ten times the solubility of mineral oil. Because moisture lowers the breakdown voltages of insulation oils and because the breakdown voltages of insulation oils do not follow a linear relationship [32,50], an empirical relationship between the breakdown voltage and increasing moisture can be found. With this link, it will be possible to create a threshold, which will be of enormous advantage to those that produce transformers using insulating palm oils. In addition, the results of other tests, both electrical and physicochemical, must also be considered. As a threshold is determined, this correlation will be useful for designers and manufacturers of palm-based insulating oils in the future.

3.2.2. Interfacial Tension

The interfacial tension test results of six palm oils and conventional mineral oils are shown in Figure 14. The conventional mineral oil has a tension of 48.46 mN/m higher than all palm oil samples. Moreover, palm oil samples PO-F, PO-E, PO-D, PO-C, PO-B, and PO-A have gradually decreasing tensions of 21.73, 17.50, 14.20, 11.43, 9.50, and 9.23 mN/m, respectively. The decrease in surface tension in palm oil is due to the properties of palm oil. When the energy state of the palm oil is lowered, there should be a corresponding reduction in the number of molecules with higher energy that are located on the border. This will unquestionably bring about a reduction in surface area. By reducing the amount of surface area, the object will have a smooth form; as a result, a great deal of energy will be gained, and gravitational potential energy will also be lowered. The tension at the surface between two distinct liquids is what causes oil and water to separate into their respective phases. This tension is caused by surface tension. The interfacial tension is high in newly obtained transformer oil, but the presence of impurities causes it to decrease. This is because oxidation lowers the interfacial tension. This phenomenon may be used for the purpose of evaluating the presence of polar pollutants as well as transformer oil degradation products [51].

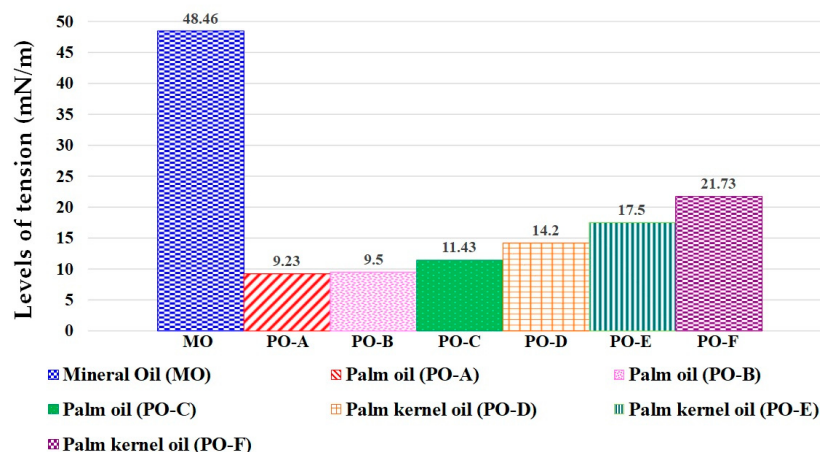


Figure 14. Comparison of the surface tension between six palm oils and conventional mineral oils.

3.2.3. Acid Values

At the same drying vacuum temperature of 60 °C, the acidities of conventional mineral oil remain at low values of 0.03 mg KOH/g, including PO-F at values of 0.059 mg KOH/g. Figure 15 shows that the PO-A, PO-B, PO-C, PO-D, and PO-E samples have high acidity values of 1.53, 1.058, 1.334, 2.626, and 0.479 mg KOH/g, respectively. The acid values seen in oil are mostly attributed to the presence of fatty acids, which are often found in the form of triglycerides. However, during the processing of oil, hydrolysis reactions often occur, resulting in the conversion of triglycerides into free fatty acids. Hence, a clear correlation exists between the acid value and the concentration of free fatty acids. This implies that an elevated acid value will result in increased levels of free fatty acids, thereby leading to

a decline in the overall quality of the oil. According to [52] AOCS (2003), the maximum acceptable amount for vegetable oil is 0.6 mg KOH/g.

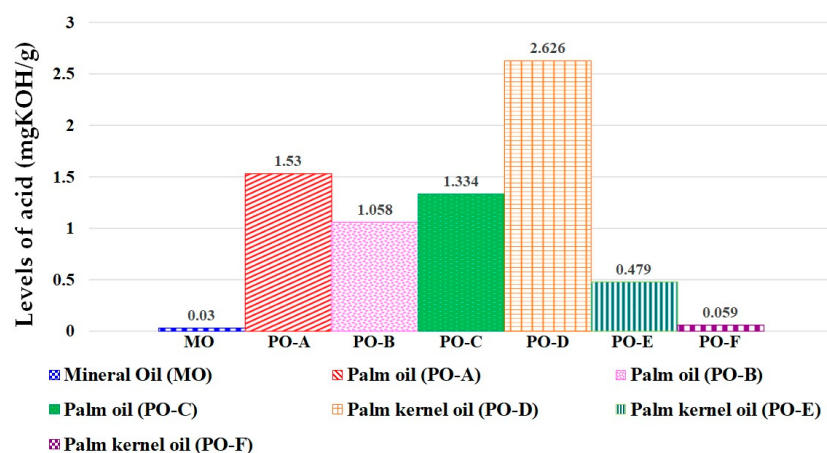


Figure 15. Comparison of the acid values between six palm oils and conventional mineral oils.

3.2.4. Ultraviolet-Visible (UV-VIS)

Figure 16 shows how the six palm oils and the standard mineral oils absorb UV-VIS light at different wavelengths before and after drying in a vacuum. It can be observed that the increase in absorbance is very slow for type A crude palm oil (PO-A, red line). The absorbance peak of the graph cannot begin to converge to a state of saturation under the wavelength range 400–600 nm in all cases, both before and after drying oil. Meanwhile, palm oil shows a different trend compared with mineral oil as a reference. The wavelengths at which palm oil absorbs light before drying under vacuum in Figure 16a are 505 nm (PO-D and PO-F), 540 nm (PO-E), 567 nm (PO-C), and 585 nm (PO-B), respectively. The increase in absorbance is quite fast for palm oil, where the absorbance peak occurs just after drying under vacuum in Figure 16b. The wavelengths at which absorbance occurs are 474 nm (PO-D and PO-F), 534 nm (PO-C and PO-E), and 582 nm (PO-B), respectively. In Figure 16, the results of this study are similar to those of the previous study [53]. For types B to F of palm oil, the same trend can be seen. But the rise in absorption for the first 500 nm in wavelengths is slower for palm oil than for mineral oil. The absorption peak also happens at a longer wavelength for palm oil than for mineral oil.

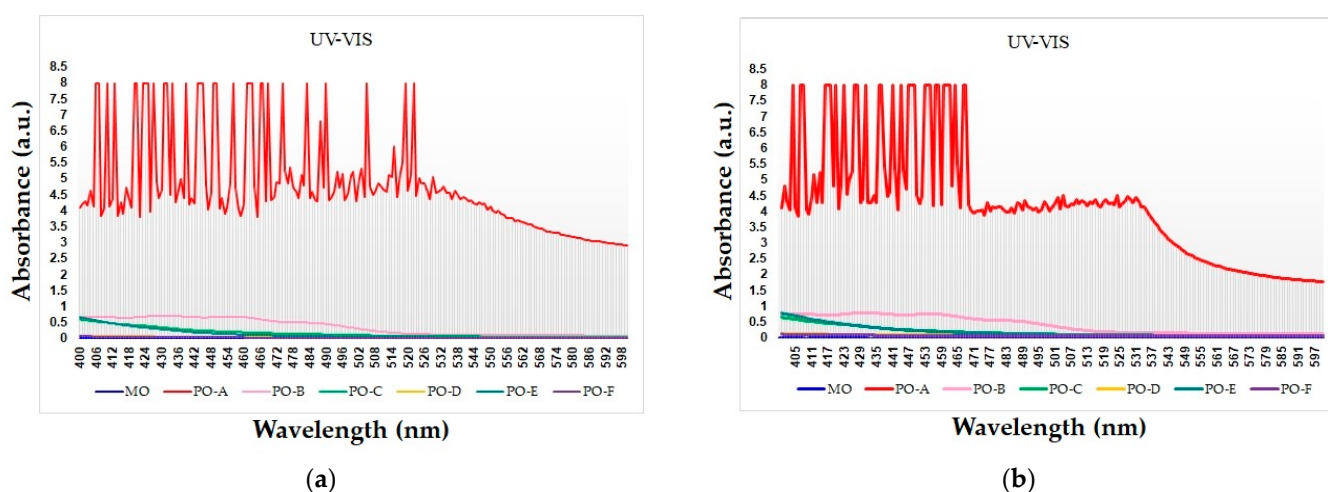


Figure 16. Variation in the UV-VIS absorbance with respect to wavelength between six palm oils and conventional mineral oils: (a) UV-VIS absorbance with liquid samples before drying under vacuum; and (b) UV-VIS absorbance with liquid samples after drying under vacuum.

3.2.5. FTIR Spectroscopy

Results analysis involves using infrared spectroscopy to identify chemical bonds within individual peaks. The six palm oil samples and one regular mineral oil, with FTIR spectra from 4000 to 600 cm^{-1} , are shown in Figure 17. Figure 17a–f displays the transmission spectra of six palm oil samples, with peaks at 2922–2921, 2853–2852, 1743–1742, 1463–1462, 1160–1159, 1152–1111, and 721–720 wavenumbers cm^{-1} , respectively. The functional groups of C-H alkanes are seen between 2850 and 3000 cm^{-1} . Alkane C-H stretches (mid to strong bonds) and carboxylic acid O-H stretches (wide and variable bonds) are represented by the transmittance peaks, and the presence of alky moieties of palmitic saturated fatty acid is substantiated by the absorption bands at 2922–2921 cm^{-1} and 2853–2852 cm^{-1} [54,55] in six palm oil samples. The C-H bonds in alkanes are quite common, making them less informative about the composition's structure. The IR peak near 1743–1742 cm^{-1} represents the functional groups ketone C=O stretch, ester C=O stretch, and carboxylic acid O-H stretch. The existence of oleic acid may be inferred from the observation of an absorption band in palm oil at a wavelength of 1743–1742 cm^{-1} , which has been attributed to C=O stretching [37,48]. In palm oil, the transmittance peaks at 1463–1462 cm^{-1} are attributed to the strength of O-H in-plane bending vibrations [32], while the wavenumber at 1111 cm^{-1} is attributed to C-O stretching, which is consistent with the characteristics of an ester group [56]. Furthermore, significant aromatic C-H bending vibrations have been observed in the functional groups between 860–680 cm^{-1} and 721–720 cm^{-1} . In addition, the FTIR spectroscopy findings for mineral oil samples are shown in Figure 17g. The transmittance peaks for the mineral oil samples are located at 2921, 2852, 1460, 1377, and 722 cm^{-1} respectively. According to their vibrational energy, the peaks on the FTIR graph indicate the various chemical substances found in the mineral oil samples. The data clearly display the distinctive absorptivity between 1470 and 1350 cm^{-1} , indicating the presence of functional groups of C-H alkane stretch, which is basically a CH_3 bond extension.

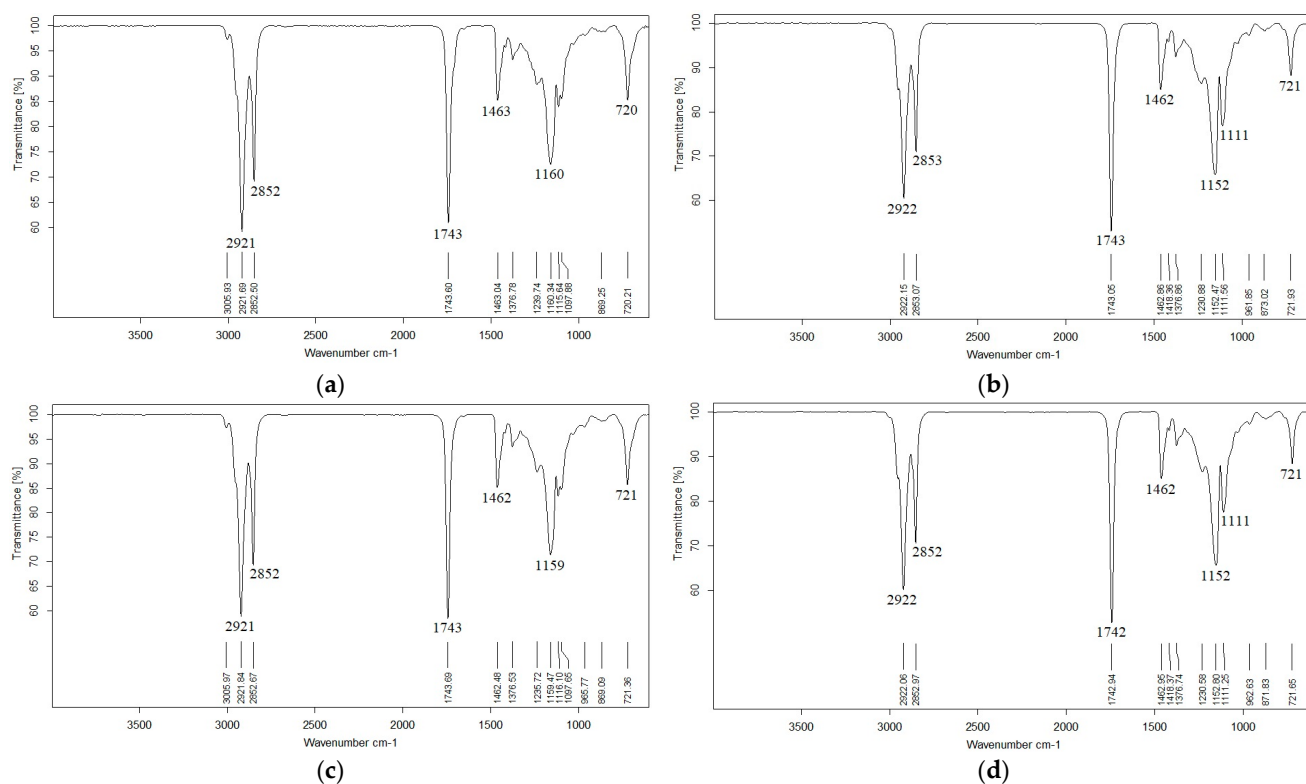


Figure 17. Cont.

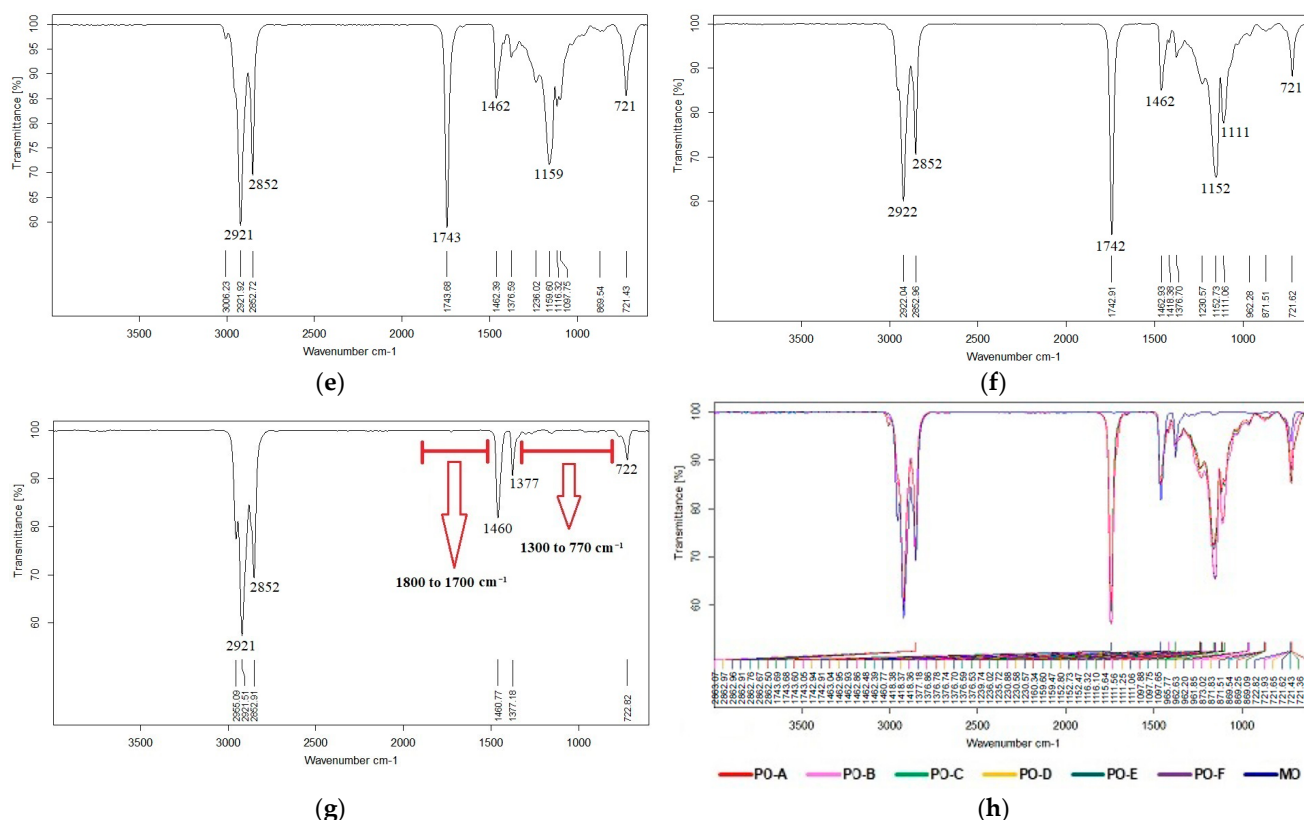


Figure 17. Variation in the FTIR spectra with respect to wavenumber of six palm oils and conventional mineral oils: (a) FTIR spectra of PO-A sample; (b) FTIR spectra of PO-B sample; (c) FTIR spectra of PO-C sample; (d) FTIR spectra of PO-D sample; (e) FTIR spectra of PO-E sample; (f) FTIR spectra of PO-F sample; (g) FTIR spectra of MO sample; and (h) FTIR spectra of all liquid samples.

Finally, the FTIR spectra findings for the six different palm oils and the standard mineral oils are shown in Figure 17h. The findings of the FTIR analysis revealed that there was no difference between any of the six palm oils. However, there is a difference in the results of the FTIR on the mineral oil sample because the mineral oil samples do not exhibit any peaks between 1800 to 1700 cm^{-1} or between 1300 to 770 cm^{-1} when compared with the six palm oil samples. According to the results of this investigation, the FTIR spectrum of an oil sample reveals that there is a shift in the chemical composition of the oil, particularly within a wavenumber range that extends from 4000 to 600 cm^{-1} .

4. Conclusions

This research presents an analysis of the electrical and physiochemical properties of six different types of palm oil in comparison to conventional mineral oil. The results revealed that natural processed crude palm oil (PO-C) had a much greater resistance to AC breakdown voltage compared to several other palm oil types, including conventional mineral oil. In addition, the results of the positive electrode lightning impulse voltage test for PO-C were still the highest compared to other types of palm oil and 58.26% higher than traditional transformer oil. In addition, in the case of negative lightning impulse voltage, PO-C has the highest value compared to other natural palm oils. However, when all palm oils were compared, it was found that they had a lower value than the traditional transformer oil. There is a difference in terms of performance between six different types of palm oil and standard mineral oil, especially on the dielectric dissipation factor, relative permittivity, and resistivity. The results show that all palm oils have a higher $\tan \delta$ than conventional mineral oils, which will result in the palm oil's insulating ability being reduced. For relative permittivity, all palm oils were compared; it was found that PO-C had a lower relative permittivity than the other oils. This could be because the fat levels in each oil were

different. Conversely, in terms of resistivity, the oil known as PO-C has the greatest value when compared to other oils. This characteristic demonstrates a strong correlation with the outcomes seen in AC breakdown testing.

In terms of physical and chemical properties, in the moisture content test on all oils, PO-C had the percentile with the highest moisture content decrease of 58.74%. In the case of testing the surface tension value, it was found that transformer oil had the highest value when compared to palm oil. On the other hand, the acidity in transformer oil is the lowest compared to all palm oils. The findings of the UV-visible spectroscopy experiment made it abundantly evident that the dielectric insulating properties of the oil enhanced after being dried in a vacuum. In addition, the findings showed that UV-visible spectroscopy was capable of qualitatively analysing the materials by aesthetically displaying the deterioration that occurred. The FTIR analysis, also assisted within a wavenumber range of 4000 to 600 cm^{-1} , indicates that there is a change in the chemical composition of the oil samples. It also assisted in determining the functional groups present in the palm oil compared with standard mineral oil. FTIR results showed no difference between the six palm oils and conventional mineral oils except for the transmission spectra, with peaks between 1800 to 1700 cm^{-1} or between 1300 to 770 cm^{-1} . There is a difference in the results of the FTIR on the mineral oil sample because the mineral oil samples do not exhibit any peaks.

Finally, results from studies in this research demonstrate the possibility of using natural processed crude palm oil, or PO-C, as a replacement for traditional transformer oil. This is consistent with the results of electrical tests that show PO-C is more resistant to voltage than other types of palm oil and more resistant than traditional transformer oil in cases of AC breakdown and lightning impulse on positive polarity.

Therefore, the findings of the tests showed that the palm oils used in this research are promising options for further development of palm oil for dielectric applications, particularly palm oil PO-C, which had promising dielectric qualities. As a result, it has potential as a replacement for conventional transformer insulating fluids. PO-C has the possibility of being developed to enhance insulation efficiency with other special materials and nanotechnology materials and testing their effectiveness before actually using them in electric transformers in the future.

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