Dielectric properties and oxidation stability assessment of vegetable-based oils as insulation for power transformers

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This paper presents laboratory investigations on 5 different vegetable-based oils and their blends to examine their long-term performance vis-à-vis their dielectric properties and oxidation under thermal ageing. The vegetable-based oil samples investigated included Canola Oil, Coconut Oil, Olive Oil, Palm Olein Oil, Sesame Oil and blends of canola and olive oil of 3 different blend ratios. The samples were thermally aged and measurement of their dielectric properties, oxidation and physical properties were conducted. Findings from this study indicated that the vegetable-based oils samples experienced more degradation (ageing) and oxidation compared to the standard mineral oil but however they exhibited high dielectric strength. Among the vegetable-based oils samples, coconut and sesame oil samples were the most aged and possessed the lowest breakdown voltage, while olive was the least aged and most stable. Sesame and canola oils experienced the highest oxidation while olive and coconut oils experienced the least. Blending of the canola and olive oils improved their dielectric properties and oxidation by as much as 37%. The finding in this study suggests that some vegetable-based oils can have good long-term performance as insulating oils. In addition, the simple and cheap blending of such oils can improve their dielectric properties and oxidation.

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1. Introduction

Power transformers are vital equipment in power systems. Causes of transformer failure are numerous, however insulation failure accounts for more the 40 % [1, 2]. Cellulose/kraft paper and oil are the two insulating materials in power transformers. The most widely used insulating oil in transformers is the mineral oil. Oil in transformer functions as both electrical insulation and cooling medium. Moisture and heat build-up are the main “culprits” in transformer oil and paper deterioration. Concerns about power transformer failure is they can lead to prolonged blackouts which can affect a large pool of power consumers. However, another current major concern about power transformers is the environmental health and risks the mineral oil pose during operation due to insulation failure. Mineral oil is non-biodegradable and toxic thus in the event of an accident such as spill or leakage takes years to degrade and harms the environment. These concerns have prompted researchers to seek biodegradable oils such as vegetable-based oils to overcome the environmental concerns of mineral oils. Literature has shown that vegetable-based oils possess the requisite qualities for use as transformer oils such as high flash point and fire point as well as high breakdown voltage and good dissipation factor (tan δ) [3 – 7]. In addition they possess better moisture absorption capability from transformer kraft paper [8]. However, compared to mineral oil, they have higher viscosity, pour point and poor oxidative stability.

Numerous studies in the past have been conducted that have shown various types of vegetable-based oils as candidates for transformer oil [9 – 19]. However, studies investigating the long term electrical and chemical performance vis-à-vis ageing and oxidative stability of these potential vegetable-based insulating oils are lacking. Furthermore, recently some researchers have reported that blending between vegetable-based oils improved their oxidative stability [20 – 21]. However, investigating their electrical characteristics has not been conducted. In view of the foregoing, there is a need to further carry out electrical and chemical studies on long term ageing characteristics of vegetable-based oils for use as transformer insulating oils.

The objective of this paper is to investigate the dielectric properties of some vegetable-based oils as insulating oils in power transformers. Additionally, this paper also investigates the dielectric properties of blended vegetable-based oil and assessed the long-term performance and stability of the vegetable-based oil as insulating oils during accelerated ageing processes.

2. Oxidative Stability of Vegetable-based Oils

There are many different types of vegetable oils in existence. Although they have been basically used in the food industry as edible oils, however due to their excellent biodegradability and lubrication performance they have also been used as lubricants [22]. At high temperatures the most prominent chemical reactions that take place in vegetable oils is oxidation. Most vegetable oils contain glycerol molecules with three long chain fatty acids attached at the hydroxy groups via ester linkages and as such can be said to be triacylglycerides [23]. The fatty acid molecules include palmitic acid, stearic acid, oleic acid, linoleic acid and linolenic acid. Palmitic or stearic acid molecules have no unsaturated carbon-carbon bonds; oleic fatty acid molecules have a single double bond (monounsaturated); while both linoleic and linolenic acid molecules have more than one double bond (polyunstaturated). Depending on the composition of the fatty acids, the vegetable oils' fatty acids are broadly classified as saturated, mono- or poly-unsaturated. Majority of vegetable oils have unsaturated bonds (double bonds). Oxidative stability of vegetable oils is greatly affected by degree of their unsaturated levels (i.e. the number of double bonds), this is due to the fact that the unsaturated carbon–carbon bonds function as active sites for oxidation and other chemical reactions such as hydrolysis due to the production of hydroxyl groups during heating or presence of oxygen [22]. The double bonds in their structures make them very unstable and the higher the number of unsaturated double bonds, the more unstable the oils becomes due to their susceptibility to oxidation.

3. Experimental Techniques

The main objective/interest of this study was to investigate and compare the long-term performance of some vegetable-based oil samples. These selected oil samples have been reported in the literature to possess insulating properties to be used as high voltage insulation particularly power transformers. To achieve the objectives of this work, the dielectric properties of the oil samples were assessed by conducting Breakdown Voltage (BDV) tests and Dielectric Dissipation Factor test (DDF). The oil oxidation was examined by Infrared Spectroscopy (FTIR). Physical properties of the oil samples such as fire point, pour point and viscosity were also carried out to complement the dielectric and oxidation measurements. Measurement for each test conducted on the oil samples was done 5 times, the average calculated and recorded.

3.1 Samples and Methodology

In this work, eight types of vegetable-based oils were used and comparison made with mineral oil. Out of the eight vegetable-based oils samples, three were blends of canola oil and olive oil at different composition. The oils samples include canola oil, coconut oil, olive oil, palm olein oil, sesame oil, and the 3 blends: CO25 Oil (75% Canola; 25% Olive), CO50 Oil (50% Canola; 50% Olive), and CO75 Oil (25% Canola; 75% Olive). Table 1 provides the fatty acid composition of the vegetable-based oil samples used in this study. The oil samples were bought off the shelf from local supermarkets in Malaysia.

Table 1. Fatty acid composition of oil samples

Oil	SFA (%)	MUFA (%)	PUFA (%)
Olive	16	75	7
Canola	7	63	30
Coconut	95	4	1
Sesame	13	41	46
Palm Olein	43	45	12

SFA – Saturated fatty acid
MUFA – Mono-unsaturated fatty acid
PUFA – Poly-unsaturated fatty acid

Before the commencement of laboratory work, the oil samples were pre-conditioned by vacuuming using a vacuum oven at low temperature. This procedure reduces the humidity of the oil that may have increased during storage in the container or moisture that may have be introduced when the oil samples were collected. The oil samples was pre-heated first until temperature of 60°C, then transferred into a vacuum where they were vacuumed for 15 minutes. Fig. 1 shows the flow chart of the entire

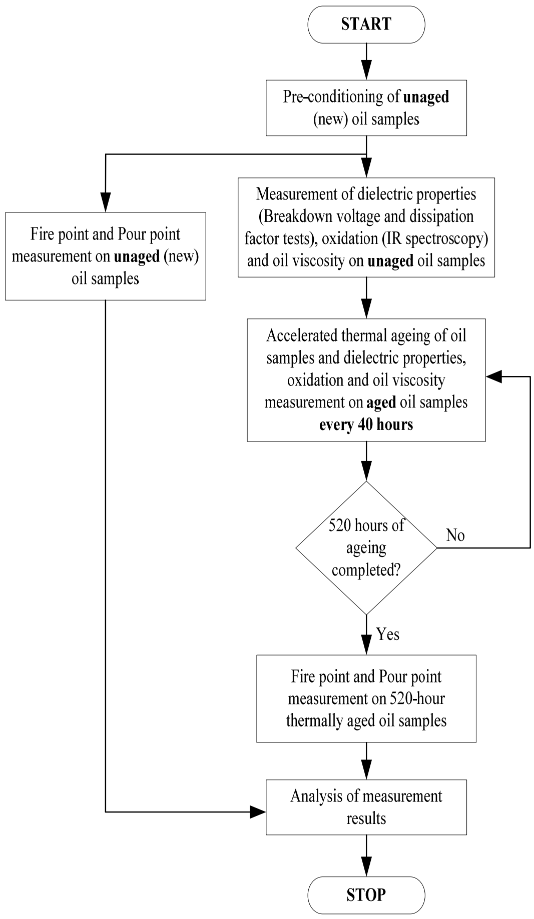

Fig. 1. Flow chart of experimental procedures

To investigate the long term performances of the vegetable-based oils samples, accelerated ageing of the oil samples was conducted. The oil samples were aged thermally using an oven, Nailik digimatic drying oven model NL 1017/C. To accelerate the ageing process, the oil samples were heated at an elevated temperature of 155°C. This temperature level is higher than the normal working temperature of power transformers which is around -20°C to 105°C [24]. The total thermal accelerated ageing duration was 520 hours. Measurements were conducted on the oil samples every 40 hours.

3.2 Measurements

ASTM D92-90 [25] method of measuring fire point was used to determine the fire points of the oil samples. Pour points of the oil samples were determined using the Auto Pour and Cloud Point Frigistat (BATH) equipment. The pour point was determined according to ASTM D97-93 [26]. A low value is desirable for transformer oil as transformers can operate in the locations that have very low temperature.

The Dielectric Dissipation Factor (Tan δ) of the oil samples was measured according to IEC 60247 [27] using a Measuring Bridge Instrument Power Supply, Tettex Instrument, model type of 2816/5284U CU YB. The oil samples were placed in test cell designed according to IEC 60247 [4] specification.

The Breakdown Voltage (BDV) of the oil samples was measured according to the International Electrotechnical Commision standard (IEC), IEC 60156 [28] using a BDV test cell designed to conform to IEC specifications. The distance between the electrodes of BDV test cell was set to 2.50 mm ± 0.005mm. High voltage was applied to the oil sample and slowly increased until breakdown occurred.

Infrared spectroscopy measurements was carried out using a FT-IR Spectrometer Perkin Elmer type. The spectroscopy results were obtained via a computer connected to the FT-IR Spectrometer. All results were retrieved from the computer saved by a software called Spectrum v5.3.1 for FT-IR spectroscopy measurements. Wavenumber value between 4000 cm-1 to 370 cm-1 was set in the Spectrum v5.3.1 to acquire the oil samples' absorbance reading.

4. Results and Discussion

4.1 Fire Point

Fig. 2 shows the results of the oil samples' fire point after undergoing 520 hours of accelerated thermal ageing. It can be seen that the vegetable-based oil samples exhibited higher fire point reading than the mineral oil before and after undergoing accelerated thermal ageing. Mineral oil is a type of crude oil also known as pure hydrocarbons. Hydrocarbon tends to react with oxygen in the air thus producing carbon dioxide and water. These reactions are exothermic, meaning they produce energy or heat. This has also been one of the reasons why petroleum based product were used widely as fuel. The same reaction also happens in vegetable-based oils. Vegetable-based oils are synthesized organic compound. However, since vegetable-based oils are fatty acids that contain –OOH bonding, more energy is needed to break the bond. This explains why vegetable-based oils samples exhibited higher fire point compared to mineral oil. With regards to the blended oil samples (CO25, CO50 and CO75), it can be seen that the blending increased the fire points of the oil sample as compared to the pure olive and canola oil samples. This shows that the blending process has improved the fire point of the oil.

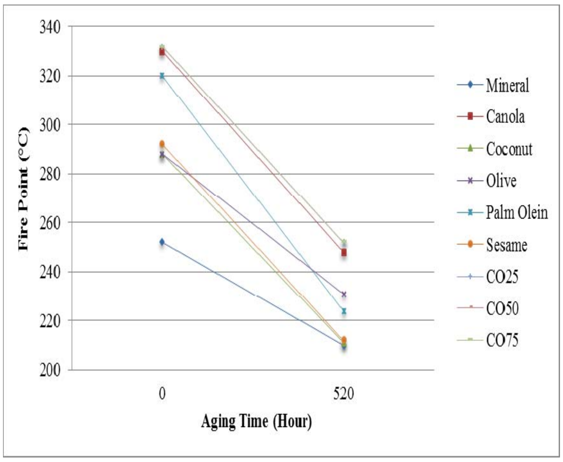

Fig. 2. Fire Point of oil samples

4.2 Pour Point

The result of the pour point measurement is summarized in Figure 3. It can be seen that the mineral oil sample had the lowest (<-33°C) pour point reading among all the oil samples. Among the vegetable-based oil samples, coconut oil had the poorest pour point value of 18°C and 24°C for new and aged respectively. Oils with high pour point values are not suitable to be use as transformer oil. This is because the oil tends to solidify at lower ambient temperature. It can also be seen from the pour point results that blending of the canola and olive oil has also improved the pour point value of olive oil. This shows that the blending process has as well improved the pour point value.

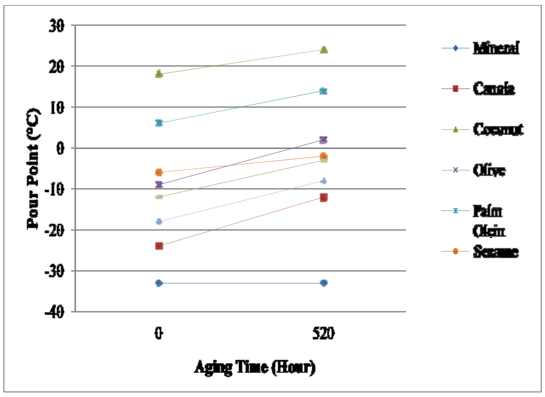

Fig. 3. Pour Point of oil samples

4.3 Dielectric Dissipation Factor

Dielectric Dissipation Factor (DDF) is a dielectric test employed to determine the ageing of the liquid and solid insulations. Figure 4 shows the plot of the DDF results against ageing time. It can be seen that the mineral oil sample did not experience much ageing. However the vegetable-based oil samples aged considerably at the end of the ageing process. This indicates that mineral oil has better long-term ageing performance compared to vegetable-based oil. Among the pure vegetable-based oil samples, sesame oil exhibited the highest DDF values implying that it was the most aged. This is because sesame oil is a poly-unsaturated oil having highest PUFA among the oil samples thus making it the most unstable because its chemical bonds can be easily broken during the ageing process due to heat application.

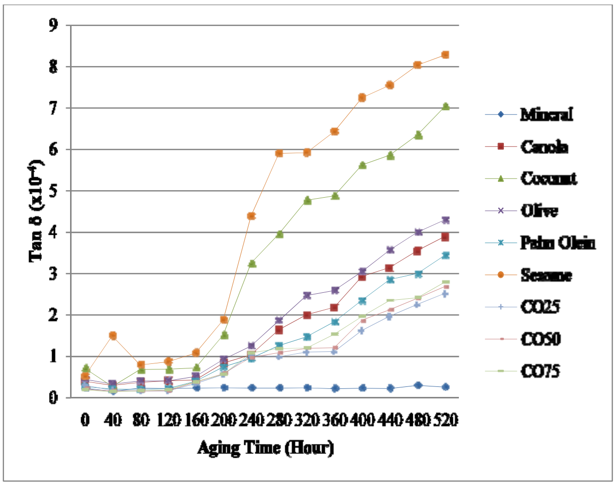

Fig. 4. Oil samples' Dielectric Dissipation Factor

Blending of the canola and olive improved the electrical performance under ageing. It can be seen that the blended samples CO25, CO50 and CO75 having DDF values of 2.5E-4, 2.7E-4 and 2.8E-4 after undergoing 520 hours of ageing were less aged compared to the pure canola and olive oil samples which had DDF value 3.9E-4 and 4.3E-4 respectively. It can be said that the blending process increased the ageing resistance of the blended oils CO25, CO50 and CO75 by 30%, 32.5% and 37.5% respectively in comparison to the pure olive and canola oil samples. Among all the tested pure vegetable-based oils samples, canola and Palm olein showed the lowest reading for tan δ. This shows that these oils are more stable when compared to other vegetable-based oil samples. When the oils were aged, their tan δ value increased much more than mineral oil implying that the resistive current (IR) flowing through the samples has increased thereby decreasing electrical resistance. This was as a result of moisture content in the environment. Moisture was absorbed by the oil samples thereby increasing the flow of resistive current. Mineral oil and vegetable-based oils absorb moisture from the environment thus having effect on the electrical properties of the oils, however vegetable-based oils absorbs moisture higher than mineral oil [29] thus resulting in higher tan δ values in vegetable-based oils during the ageing process.

4.4 Breakdown Voltage

The results obtained for the BDV of the oil samples are shown Figure 5. In general it can be seen that the thermal ageing has caused a reduction in the breakdown voltages of all the oil samples. Most of the vegetable-based oils had higher BDV than mineral oil both at the beginning and after they had undergone thermal ageing. The vegetable-based oils samples have a good BDV for use as transformer oil.

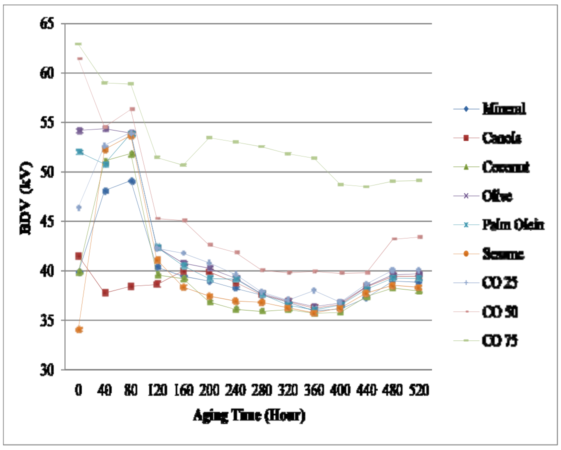

Fig. 5. Breakdown Voltages of oil sample

However, even though the mineral oil was among the oil samples that had low BDV, it showed a slight reduction in its BDV at the end of the ageing process. Most of the vegetable-based oils samples showed a significant reduction in their BDV at the end of the ageing period.

DV reading for oil is closely related to the level of moisture environment. Although vegetable-based oil absorbs moisture higher than mineral oil, however the mineral oil sample had lower BDV value even at lower moisture conditions. This is probably due to the fact that vegetable-based oils are fatty acid esters thus when they absorb moisture, the water molecules in the moisture are strongly trapped by the fatty acid esters molecules. This explains why fatty acid esters have greater resistance to electrical breakdown than mineral oil [29].

With regards to the blended vegetable-based oils samples, blending improved the BDV of the pure oil samples (canola oil and olive oil). It can be seen from the graph of Figure 4, oil samples CO25, CO50 and CO75 after ageing had BDV values of 40.03 kV, 43.42 kV and 49.13 kV respectively higher than the pure canola and olive oil samples (39.46 kV and 39.7 kV). It can thus be said that the blending process increased the dielectric strength of the 3 blended oils by 2.56%, 10.26% and 25.64%.

4.5 Kinematic Viscosity

The results of the kinematic viscosity of all the oil samples are summarized in the Table 2. It can be seen from Table 2, mineral oil had the lowest viscosity value among the oil samples. The vegetable-based oils samples had high viscosity values greater than 11 cP. Among the vegetable-based oils samples, coconut oil had the lowest viscosity reading while palm olein oil had the highest. The desirability of lower viscosity of insulating oils in transformer is for the purpose of heat convection. From the vegetable-based oils samples, it can be said that palm olein oil may not be suitable due to its large viscosity value. However, to assess the effect of long term ageing in the oil samples, Figure 7 shows the viscosity increase (in %) of each oil after undergoing the ageing process.

Table 2. Kinematic Viscosity of Oil samples

Oil / Viscosity (cP)	Ageing Time (Hour)													
	0	**40**	**80**	**120**	**160**	**200**	**240**	**280**	**320**	**360**	**400**	**440**	**480**	**520**
Mineral	4.66	4.70	4.89	4.83	4.74	4.88	4.83	4.75	4.66	4.75	4.79	4.94	5.17	5.46
Canola	16.75	16.80	18.53	18.61	18.46	18.64	18.37	18.11	18.32	17.89	18.32	18.53	19.07	18.91
Coconut	12.09	11.34	13.24	12.37	12.15	12.65	12.5	12.52	12.93	13.11	13.48	13.82	14.10	14.26
Olive	18.88	17.50	17.67	17.74	17.68	17.83	17.64	17.72	17.87	18.03	18.34	18.62	18.67	19.39
Palm Olein	19.34	18.07	17.67	18.27	18.06	18.51	18.46	18.59	18.69	19.35	19.73	19.84	20.25	20.44
Sesame	14.33	16.63	15.19	16.39	15.69	16.27	16.06	15.80	16.14	17.14	17.26	17.48	17.58	17.87
CO25	17.27	16.63	17.89	16.86	16.63	17.05	16.97	17.10	17.26	18.32	18.43	18.62	18.79	18.95
CO50	17.63	17.21	17.15	17.59	17.52	17.66	17.62	17.48	17.66	18.47	18.50	18.80	18.92	19.04
CO75	17.90	17.38	18.01	17.82	17.91	17.94	17.85	17.94	18.00	18.93	19.01	19.13	19.22	19.27

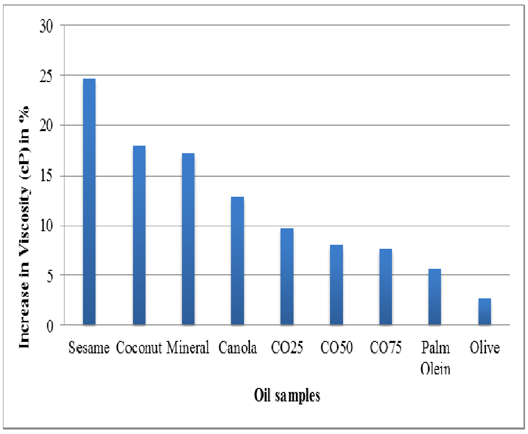

Fig. 7. Kinematic Viscosity increase (in %) of oil samples

It can be seen that the viscosity of olive oil sample was the least affected by the thermal ageing process followed by palm olein, although it possessed the highest viscosity value. Mineral oil, which has the lowest viscosity value among all the oil samples had a high percentage increase in its viscosity value as well. Among all the pure oil samples, sesame showed the highest increase in viscosity. Sesame oil shows a very high increase in viscosity reading because it is a poly-unsaturated oil. Its chemical bonding is more easily altered during heating process. The change in viscosity indicates significant structural changes. This has been attributed to polymerization and the formation of high- molecular-weight compounds via carbon-to-carbon and/or carbon-to-oxygen-to-carbon bridges between fatty acids. For olive oil, it is categorized as mono-unsaturated where only single bonds for carbon-carbon bonds are present in the chain thus making it very stable. Blending of the oils slightly improved their viscosity. It can be seen from Table 2 that the blended oil samples had lower viscosity that pure olive oil. In addition, the blending reduced the rate of increase in viscosity of pure canola oil sample as can be seen in Fig. 6. The oil samples CO25, CO50 and CO75 after ageing had % increase in viscosity values of 9.73%, 8% and 7.65% respectively while pure canola oil sample which was 12.9%.

4.6 Infrared Spectroscopy

FTIR measurements on the oil samples showed that the oils samples had similar IR spectra thus implying that he oils samples have similar chemical structures. From the IR spectra it was observed that for all oil samples, there was a continuous increase in their IR absorbance values at the absorption peak 3475 cm-1. The region 3550 – 3230 cm-1 is usually associated with the hydroxyl groups (O-H functional groups) [30]. This continuous increase in the hydroxyl absorbance indicates that the oil samples have experienced oxidation due to hydrolysis reaction that took place as a result of the heating [23]. Figure 8 shows the IR absorbance readings of all the oil samples throughout the accelerated thermal ageing process.

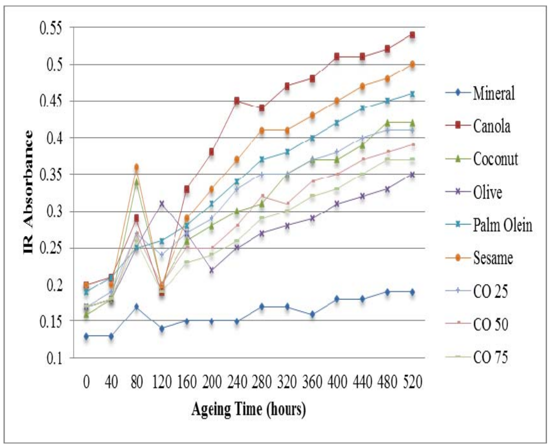

Fig. 8. IR Absorbance (at wavenumber 3475 cm-1) of oil samples

It can be seen that the increase in IR absorbance value for mineral oil was from 0.13 to 0.19. This small increment in the IR absorbance value indicates that mineral oil experienced a very slow oxidation process and is stable. However, this was not the case for the vegetable-based oils. All the samples' IR absorbance values increased sharply, indicating very high oxidation process. Canola oil experienced the highest oxidation (0.20 to 0.54), implying that among the oil samples, it is the most unstable. On the other hand, olive oil was the least oxidised among the vegetable-based oils samples (0.17 to 0.35). This indicates that olive oil is the most stable among the vegetable-based oils samples. Although both canola and olive oils are categorized as mono-unsaturated oil, however the poly-unsaturated levels of canola oil are higher than that of olive oil thus making it less stable than olive.

With regards to the blended oils samples, it can be seen that the process has also improved the oxidation stability of the oils. The oil samples CO25, CO50, and CO75 oil showed lower increment in IR absorbance reading than the original oil, canola oil. The blended oil samples CO25, CO50, and CO75 had IR absorbance readings of 0.41, 0.39 and 0.37 respectively, while the pure canola and olive oil samples had 0.54 and 0.35. The blending process reduced the rate of oxidation in increase in canola oil by 24.57%, 37.98% and 40.7% according to the blend composition. Thus it can be said that blending canola (unstable oil) with olive (stable oil) improved the oxidation stability of the former.

5. Conclusions

The dielectric properties of 5 different types of vegetable-based oils as well as their blends during thermal ageing process to assess their long-term performance and stability have been investigated and the experimental results presented in this paper. The main findings are as follows:

1. The long-term electrical and chemical properties of mineral and vegetable-based oils samples showed that, overall, mineral oil performed better than the five different types of vegetable-based oils samples. Changes in the dielectric properties of mineral oil were not significant indicating the oil did not undergo considerable degradation and is quite stable.
2. The vegetable-based oils samples showed a significant change in their dielectric properties, thus implying that the accelerated thermal ageing has greatly affected their insulating properties.
3. Among the vegetable-based oils samples investigated, sesame and coconut oil samples were the most degraded after the undergoing thermal ageing, while olive oil was the least affected and most stable at the end of the accelerated ageing process.
4. Blending of vegetable-based oil samples improved their dielectric properties and oxidation stability during the accelerated ageing process.

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