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Electrical Analysis of Ceiba Pentandra Oil as a Replacement for Mineral Oil in High Voltage Insulation Application

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***Abstract**: The application of Ceiba Pentandra Oil is introduced as an alternative to the traditional non-biodegradable insulation oil. Through the recent research in vegetable based insulation oil (coconut oil, palm oil, and olive oil), it is identified that the vegetable insulation oil is biodegradable but edible in nature, which leads to the food crisis. To prevent the insufficiency of food, an interesting non-edible oil is extracted from the seeds of Ceiba Pentandra, which has the capability of biodegradation. This work has focused on the utilization of Ceiba Pentandra seeds for the production of vegetable based insulation oil since it is considered as the sustainable energy resource and. A two-step chemical conditioning method and antioxidants are used to produce the Processed Ceiba Pentandra oil (PCPO). Adding to that, the insulation behavior of Processed Ceiba Pentandra oil (PCPO) with and without antioxidant is analyzed. The different concentrations of PCPO and naphthalene based Mineral oil mixtures have been compared as per the ASTM standard. The two-step chemical conditioning method has provided the enhanced behavior of physical properties like Viscosity, Acidity, Flashpoint, Fire points and AC breakdown voltage. While improving the oxidation stability, the electrical property like AC Breakdown voltage has met the dielectric Standards. Thus this Processed Ceiba Pentandra oil (PCPO) has the potential to be an alternative of traditional insulation oil.*

***Keywords:** biodegradable oil, power transformer, breakdown Voltage, physicochemical and electrical properties*

1. Introduction

The electrical power system has taken a magnificent role in the recent days since the necessity of this system in industrial applications has remarkably increased. The transformer and circuit breakers are regarded as its paramount components. There are variety of transformers have been used in electrical power system, among which, the liquid cooled transformer is highly preferable since it provides high efficiency with high loading capacity. The insulating oil has the capability of Electrical Insulation and heat transfer in both the liquid cooled transformers and circuit breakers. The mineral oil is commonly utilized as the insulating oil for more than100 years. This mineral oil is actually a liquid hydrocarbon, which has paraffinic or naphthalene structure and it is acquired through the fractional distillation of crude petroleum. Though it provides certain beneficial features like great dielectric strength, high oxidation stability, minimal viscosity and good heat transfer capability, it has low biodegradability i.e., < 25 % [1-3]. Due to the lack of availability and high cost of petroleum products, the price of mineral oil gets increased, which has promoted the researchers to focus on the natural insulating oil. Thus various researches have been done in vegetable based insulation oil since it has certain beneficial features like biodegradable nature, fire resistance and accessibility [4-8]. Multiple researches have been done by using vegetable oils including palm oil, sunflower oil, olive oil, rapeseed oil, coconut oil and so on; they have been tested successfully in various voltage levels [9]. In spite of the fact that these vegetable oil has provided advantageous impacts, it leads to the big trouble of food insufficiency, because of which the researchers have turned their attention to non-edible vegetable oil [10-11].

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Various researches have been made with the non-edible oil like Jatropha curcas, Pongamiapinnata and Castor oil. The Jatropha curcas seeds are preferably used in various places and the oil is extracted through the two way chemical process and it provides better results. However, it is not possible to implement this oil extraction process in certain places, which have four different seasons since the yielding of this seed is seasonal [12]. Castor oil is considered as one of the significant non-edible oils, which is extracted from the seeds of Ricinus Communis plant through the chemical process of trans-esterification. In spite of the beneficial impact of this oil, the direct use of this oil in the injection engine is not possible since it has extreme viscosity [13]. To overcome all these issues, Ceiba Pentandra or Kapok oil is preferred and the Two-step trans-esterification is employed as a chemical process of oil extraction, which aids in the reduction of FFA in the oil [14].

The Oxidative stability of natural ester relies on its composition of free fatty acid and the natural esters like coconut oil, rapeseed oil, sunflower oil have contained free fatty acids as like the Ceiba Pentandra Oil, which reduces the oxidation stability. Nowadays more natural and synthetic oxidative inhibitors are available and they are tested with the Natural ester. The Oxidative stability has been enhanced by including suitable antioxidant [15].

The main purpose of the work is to introduce a new vegetable based insulating oil called Processed Ceiba Pentandra oil (PCPO). In this work, the insulation behavior of Processed Ceiba Pentandra oil (PCPO) is investigated with/without antioxidant and with different concentration of PCPO/MO oil mixtures. In this work, the physicochemical properties like viscosity, flash point, fire point, water content, acid value and Electrical property of Break down voltage are investigated. A traditional naphthalene based mineral oil is taken into account for comparison.

2. Materials and methods

2.1. Ceiba pentandra oil

The Malvaceae family, which includes Ceiba Pentandra or kapok, is well-known in Southeast Asia, India, Sri Lanka, and Northern America. This tree has a long growth cycle and is popular due to the non-edible oil seeds it produces. These seeds are typically utilized in the manufacture of soap and biodiesel because they have high oil content and free fatty acid content [16]. Farmers can grow these seeds on bare, bare ground with great ease because this tree requires less moisture. Thus, it is widely accessible.

Extraction of oil

The Ceiba Pentandra seed pods were gathered from an area in Tamilnadu, India known as the erode. The 100-200 kapok seeds in each seed pod have a silky fiber covering that can be easily removed by hand picking. Mechanical extraction and solvent (chemical) extraction are the two major methods that are routinely employed for the commercial oil extraction of kapok. Mechanical pressing is one of these methods. However, because solvent extraction requires costly and dangerous chemical solvents, it has only been used in large-scale enterprises [17].

Ceiba Pentandra seeds have been either dried out in the sunlight for three weeks or dried out in an oven at 60ºC for 12 h, then these seeds are given into the high pressure mechanical screw and through this continuous pressure, the oil is extracted from the seeds. The extracted oil is filled with scraps and sediments and to remove them, the extracted oil is fed to the filter bag. Once the filtration process is complete, the oil is simply allowed to settle for a few hours, during which time the unfiltered contaminants have been eliminated. Last but not least, free fatty acid content is added to the refined oil, which is produced with a pale yellow color [18] and has high viscosity, high acidity, and low dielectric strength as a result. The Physic-chemical properties of the crude Ceiba Pentandra Oil are listed out in Table 1.

Table 1. Crude CPO – properties

Property	Value
Relative density (g/cm^3)	0.92
Kinematic Viscosity 40ºC	30-40
Water content [ppm]	918
Acid Value [mgKOH/g]	29.42
Flash point [ºC]	290
Fire point [ºC]	315
Breakdown Voltage [KV]	25-35

Though the crude Ceiba Pentandra Oil has high flash point and fire point, it has average breakdown voltage, poor viscosity and poor acidity. Low viscosity is necessary for high heat transfer, whereas chemical modification is crucial for high dielectric strength and low acid number. Thus, to achieve oxidative stability, natural antioxidants have been added to the crude Ceiba Pentandra oil and it has undergone a second round of chemical processing. Table 2 [19] shows the composition of free fatty acids.

Table 2. Free fatty acid composition of crude

Fatty acid	Myristic	Palmitic	Stearic	Oleic	Linoelic	Arachidic
Formula	$C_{14}H_{28}O_2$	$C_{16}H_{32}O_2$	$C_{18}H_{36}O_2$	$C_{18}H_{34}O_2$	$C_{18}H_{32}$ O_2	$C_{20}H_{40}O_2$
Structure	C14:0	C16:0	C18:0	C18:1	C18:2	C20:2
Composition	0.16	23.26	2.55	21.88	38.92	1

2.2. Chemical process - esterification

By adding alcohol to the oils while using a catalyst, the organic process of esterification has boosted the yielding potential and reaction speed. This process involves treating reactants such carboxylic acid (R-COOH) with alcohol (R-OH) while a catalyst is present, resulting in the formation of an ester (R-COO-R). Similar to this, trans-esterification reduces the viscosity of triglycerides by chemically converting free fatty acids (FFA) into mono esters. The two-step trans-esterification method has been used to produce ester from FFA oils [20]. They are,

a) Acid esterification: This is the first step in trans-esterification process, where the acid is used as a catalyst, which has reduced the FFA content of Ceiba Pentandra oil to less than 2%.

b) Alkaline esterification: In this step, the alkaline is used as a catalyst that converts the low FFA Ceiba Pentandra oil into its mono ester.

a) Acid esterification

Generally, the Acid esterification has been performed to reduce the FFA value of Ceiba Pentandra oil below 2% by using acid as a catalyst. Initially there is 14.71% of FFA content and 29.42 mg KOH/gm of acid value in Ceiba Pentandra oil. The excess amount of FFA has caused huge impacts in alkali-esterification process as it reacts with alkali catalyst and forms the soap. This soap formation prevents sustainable extraction of oil from the fraction. Thus the FFAs can be pretreated by using acid catalyst (H_2SO_4) to reduce the acid level of Ceiba Pentandra oil as below 2 mg KOH/gm. In acid esterification, the mixture of Ceiba Pentandra oil, alcohol and sulphuric acid are taken into account. The sustainable amount of Ceiba Pentandra oil is collected in a reactant flask and it is heated to its optimum temperature value. The preheated Ceiba Pentandra oil is treated with methanol and sulphuric acid; on the other hand, the temperature has to be maintained to 60^{o}C. The entire mixture has to be stirred properly with magnetic stirrer at the speed of 500-600 rpm. Then the product has to be allowed to settle down for 2 h, through which the excess methanol, impurities floating on the top surface and the low free fatty acid have been settled down at the bottom. The low free fatty acid is separated from the funnel and it is heated up to 70^{o}C to remove the excess methanol content and then it is washed with distilled water to extract the additional impurities. Therefore, the acid value of the oil gets minimized.

However, the acid esterification has been affected by molar ratio, amount of acid catalyst, temperature and reaction time. The first and foremost factor is molar ratio that affects acid esterification during the reduction of acid value. The methanol to oil ratio is considered as Molar ratio, hence the acid catalyst esterification has increased with the raise of methanol value. The second major factor that affects the process is the amount of acid catalyst on the acid value. The esterification process increases through the increase in the amount of catalyst. The next parameter that affects the esterification process is temperature. The rate of reaction has increased with the raise in temperature rate. The final factor that affects the process is reaction time. In first 45 min, the rate of reaction is fast and it slows down after 45 min.

b) Alkaline esterification

When the acid esterification process is over, the impurities are removed in Ceiba Pentandra oil and it has been trans-esterified to fatty acids' mono esters with the aid of alkaline catalyst. The low free fatty acid is taken in a flask and stirred well by using magnetic stirrer. A freshly prepared Potassium hydroxide methanol solution is used to have optimum catalytic activity and that has been added with Ceiba Pentandra oil at 60^{o}C under constant stirred state, where the time calculation has taken place. After that, the entire mixture can be stirred well for about 45min at the same temperature and then it has been transferred to a separating funnel, in which the methyl ester is floating on the top layer and glycerol has settled down at the bottom. The glycerol is filtered out and it can be used as a by-product in pharmaceutical and cosmetic production. The methyl ester is filtered and the warm water is slowly sprinkled on it. Finally the excess methanol and water can be removed by heating the substance under 110^{o}C and then it is allowed to cool at room temperature. As like acid esterification, alkaline esterification can also be affected by four major factors such as influence of molar ratio on oil conversion efficiency, amount of alkali catalyst, reaction temperature and time.

When the above mentioned two-step trans-esterification process is done, the pale yellow color has been turned into mild yellow and the excessive water content is removed by the process of heating. This chemically treated Ceiba Pentandra oil is known as Processed Ceiba Pentandra oil (PCPO).

2.3 Antioxidants

Antioxidants are substances that prevent the auto-oxidation of natural esters by providing free radicals their hydrogen during auto-oxidation. More synthetic and natural antioxidants are required to combat the free fatty acid concentration and easy oxidation of natural ester. The two most widely utilized synthetic antioxidants are butylated hydroxy anisole (BHA) and butylated hydroxy toluene (BHT). The oxidative stability has recently been increased using a natural antioxidant, and an environmentally friendly -Tocopherol has been chosen for having strong oxidative stability [21, 22].

2.4. Sample illustration

A 500 mL of Processed Ceiba Pentandra oil (PCPO) is taken into a conical flask, which has been heated under the required temperature to dissolve the antioxidant. The required amount of Alpha Tocopherol $C_{31}H_{52}O_3$ is added, through which the oil has been heated and a magnetic stirrer is used for the proper dispersion. Similarly PCPO/MO mixtures have been prepared by adding suitable volume of Mineral oil to the heated Processed Ceiba Pentandra Oil (PCPO) and a magnetic stirrer is used for the proper agglomeration. The type of the sample and the volume of added antioxidant are given in Table 3.

Table 3. Sample type and volume of antioxidant

Types	Sample	Volume of additive antioxidant
I	S 1	CCPO
	S 2	PCPO
	S 3	PCPO+1gm α-tocopherol
	S 4	PCPO+2gm α-tocopherol
	S 5	PCPO+5gm α-tocopherol
	S 6	100% MO
II	S 7	50% MO + 50%PCPO
	S 8	40% MO + 60% PCPO
	S 9	30% MO + 70% PCPO
	S 10	20% MO + 80% PCPO

Experimental procedure

Viscosity

The factor, which resists the flow of liquid is termed as viscosity. According to the ASTM D445, the The factor, which resists the flow of liquid is termed as viscosity. According to the ASTM D445, the viscosity test is conducted for both the sample of crude and processed Ceiba Pentandra Oil. Redwood Viscometer is employed to calculate the viscosity of the oil. The oil sample of 50 mL is filled in the apparatus, which is attached with a thermometer and it has been heated in 40°C. When the temperature reaches a certain point, the lock is opened to flow the oil out. Simultaneously the time, which is taken for the discharging of 50 mL oil is noted to calculate the viscosity, where the Standard value for the new natural ester is 50 and mineral oil is 12.

Total acid number

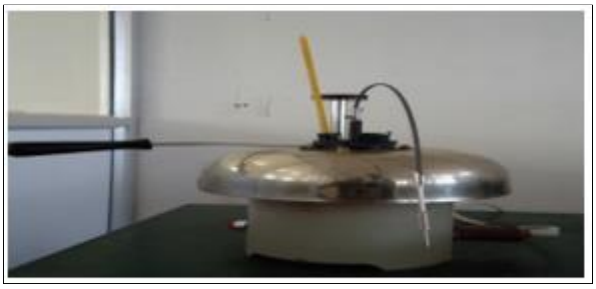
The amount of potassium hydroxide in milligrams is regarded as the total Acid Number, which is used to neutralize the acid per gram of sample. The acid value in natural ester is mainly estimated through the processes like hydrolysis, pyrolysis and oxidation. The high acid value has led to corrosion and sludge formation, along with that, the Potentiometric end point titration method is used to measure the acid number mg KOH/g in the sample. As stated in ASTM D664, the neutralized number is measured for both the sample of crude and processed Ceiba Pentandra oil. The standard value for new natural ester is 0.06 mg KOH/g and mineral oil is 0.03 mg KOH/g.

Water content

The electrical characteristics of an insulating liquid is decreased when the dissolved water gets increased. As stated in ASTM D1533, the dissolved water content of both the crude and processed Ceiba Pentandra oil have been measured; An Automated Coulometric Karl Fischer titrator is used for measuring the water content of samples in the form of mg/kg (ppm). The standard value of new natural ester is 300 mg/kg (ppm) and mineral oil is 35 mg/Kg (ppm).

Flash and fire point

At the lowest liquid temperature, the sample oil gets vaporized to light a short-term fire on the surface of the oil, which have lasted for less than 1s and the temperature, in which this process takes place is regarded as the Flash point. A Cleveland open cup tester with suitable high value thermometer is used for the measurement of flash point for both the sample of crude and processed kapok oil as stated in ASTM D92.



At a particular temperature, the sample oil gets vaporized to burn and the burning sustains for at least a minimum of 5s. The temperature, in which this process takes place, is regarded as the fire point. A Cleveland open cup tester with a thermometer is used for the measurement of fire point for both the sample of crude and processed kapok oil as stated in ASTM D92. The standard value for flash and fire point of new natural ester is 275ºC and 300ºC respectively.

AC Breakdown voltage

Breakdown voltage testing has been conducted on the basis of ASTM D1816 by using a test cell of 0.95L capacity. Two brass spherically capped electrodes with 25mm radius have been arranged horizontally with the gap of 2mm, which have been mounted in the opposite sides with the adequate gap. Before using these electrodes in the test, they are cleaned with volatile solvent and polished with a soft cloth. Then the oil samples are slowly poured into them. There has to be a gap of 10 min between the process of oil filling and voltage application since it is essential for the air bubbles in the oil to get released from it. The voltage has to be applied at the rate of $0.5Kv$ per second and it has to be increased from zero to the rated voltage until the occurrence of breakdown takes place. Five different breakdowns with the interval of 1min have been taken on one sample for the successive breakdowns. The average of these five values is considered as the dielectric breakdown voltage. The ideal value for new natural ester is $45kv$ and mineral oil is $35kv$.

3. Result and discussions

PCPO with antioxidants

The physicochemical properties of Crude CPO is disclosed in Table 1 and the PCPO with and without Alpha Tocopherol oxidation inhibitor is disclosed in Table 4. The chemical conditioning procedure has improved the physicochemical properties and the Alpha Tocopherol has significantly improved the electrical properties of the oil.

Table 4. Properties of PCPO- with and without Alpha Tocopherol

Sl. No	Sample Name	Kinematic Viscosity @40 °C	Total Acid Number mg KOH/g	Water content [ppm]	Flash point [°C]	Fire point [°C]	AC BDV [kV]
1	Crude Ceiba Pentandra Oil [CCPO]	37 37	29.42	918	290	315	36
2	Processed Ceiba Pentandra oil [PCPO]	26	0.087	360	279	308	42
3	Mineral oil [MO]	9 9	0.021	15.3	147	165	50
4	PCPO+ 1gm α-Tocopherol	20 20	0.054	290	257	265	46
5	PCPO+ 2gm α-Tocopherol	22 22	0.058	222	265	271	51
6	PCPO+ 5gm α-Tocopherol	24 24	0.073	188	274	278	49
7	IEEE std C57.147-2018	< 50	< 0.06	< 300	> 275	> 300	> 45
8	IEEE std C57.106-2015	< 12	< 0.03	< 35	> 145	> 145	> 35

From Table 1 and Table 4, the first conditioning procedure has clearly mentioned the dropping of kinematic viscosity from 37-26 cSt and it is done by removal of phospholipids, which provides the high heat transfer capability. The second important note is that, the conditioning procedure has reduced the acid value from 29.42mg KOH/g to 0.087 mg KOH/g; though this value is close to the ASTM Standard specified value of natural ester oil 0.06 mg KOH/g, it is higher than the standards. After the conditioning process, the Flash point of Ceiba Pentandra oil is decreased from 290°C to 279°C but it has satisfied the specified limit of 275°C as per the ASTM Standard. The Fire point of Ceiba Pentandra oil is also decreased from 315°C to 308°C after the conditioning process yet it has satisfied the specified limit of 300°C as per the ASTM Standard. The water content is increased by the chemical processing and to minimize the water content, the oil has been dried out with silica gel pellets at the ratio of 1g of silica to 100 mL of oil under continuous stirring of 500 rpm for 1 h. Figures 1a to 1f have highlighted the graphical representation of the results of the Physical properties of PCPO with Alpha Tocopherol.

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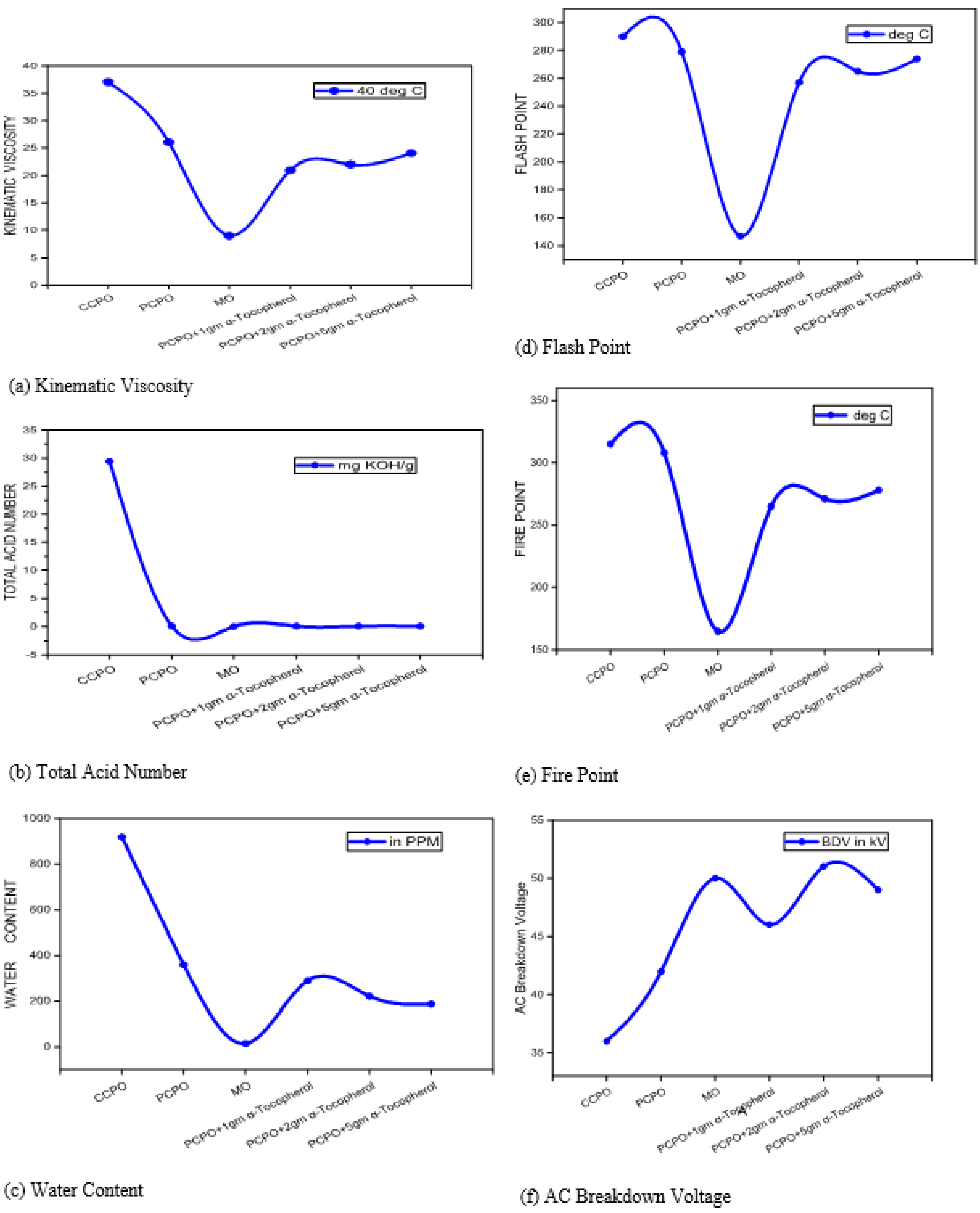

Figure 1. Various concentration of Alpha Tocopherol with PCPO

The breakdown Voltage of PCPO with Alpha Tocopherol has been increased significantly. The dielectric breakdown strength of crude Ceiba Pentandra oil is $36Kv$ and then the conditioning process has improved it to 42 kV. After adding different concentration of Alpha Tocopherol, the breakdown voltage of PCPO oil is improvised, which is close to the ASTM standards. Figure 1f shows the Dielectric breakdown strength of various concentration of Alpha Tocopherol with PCPO.

PCPO/MO mixtures

The physicochemical properties of Crude CPO is disclosed in Table 1 and the PCPO/MO mixture is disclosed in Table 5. The ideal specifications of MO and new natural ester oil are provided for the purpose of comparison. The chemical conditioning procedure has improved the physicochemical properties; different concentration of Mineral Oil mixtures have improved the electrical properties of PCPO oil [22].

The samples with different proportions of PCPO/MO mixtures have been examined, through which the dropping of kinematic viscosity, acid value, Water Content, Flash Point, Fire Point and the Breakdown Voltage have been analyzed. The various concentrations of PCPO/MO mixture includes 50% MO + 50%PCPO, 40% MO + 60%PCPO, 30% MO + 70%PCPO and 20% MO + 80%PCPO. The outcomes of all these proportions have been analogized with the standard values of IEEE std C57.147-2018. The result of this experimental investigation has proved that the mixture with the proportion of 40% MO + 60%PCPO has met the ideal values of ASTM Standard. In this combination, the kinematic viscosity is dropped from 26 cSt to 19 cSt, which provides the high heat transfer capability. The conditioning procedure has reduced the acid value from 0.087mg KOH/g to 0.06mg KOH/g, which is equal to the ASTM Standard's specified value of natural ester oil. After the conditioning process, the Flash point of Ceiba Pentandra oil is decreased from 279^{o}C to 226^{o}C and the Fire point is decreased from 308^{o}C to 252^{o}C .The water content is increased by the chemical processing and to reduce the water content, the oil has been dried out with silica gel pellets at the ratio of 1g of silica to 100 mL of oil under continuous stirring of 500 rpm for 1h. Figures 2a to 2f have highlighted the graphical representation of the results of the Physical properties of PCPO/MO mixtures.

Table 5. Properties of PCPO with and without mineral oil

Sl. No	Sample Name	kinematic Viscosity @40 ºC	Total Acid Number mg KOH/g	Water content [ppm]	Flash point [ºC]	Fire point [ºC]	AC BDV [kV]
1	100% MO	9	0.021	15.3	147	165	50
2	100% PCPO	26	0.087	360	279	308	42
3	50% MO + 50%PCPO	17.2	0.054	187	213	236	48
4	40% MO + 60%PCPO	19	0.06	230	226	252	45.2
5	30% MO + 70%PCPO	21	0.067	256	238	265	44
6	20% MO + 80%PCPO	22.6	0.073	291	253	279	43.5
7	IEEE std C57.147-2018	< 50	< 0.06	< 300	> 275	> 300	> 45
8	IEEE std C57.106-2015	< 12	< 0.03	< 35	> 145	> 145	> 35

The breakdown Voltage of PCPO/MO has been increased significantly. The dielectric breakdown strength of crude Ceiba Pentandra oil is $36Kv$ and then, the conditioning process has improved to 42 kV. After adding different Concentration of MO, the breakdown voltage of PCPO/MO oil is slightly greater than the IEEE standard. Figure 2f shows the Dielectric breakdown strength of various concentration of PCPO/MO mixtures.

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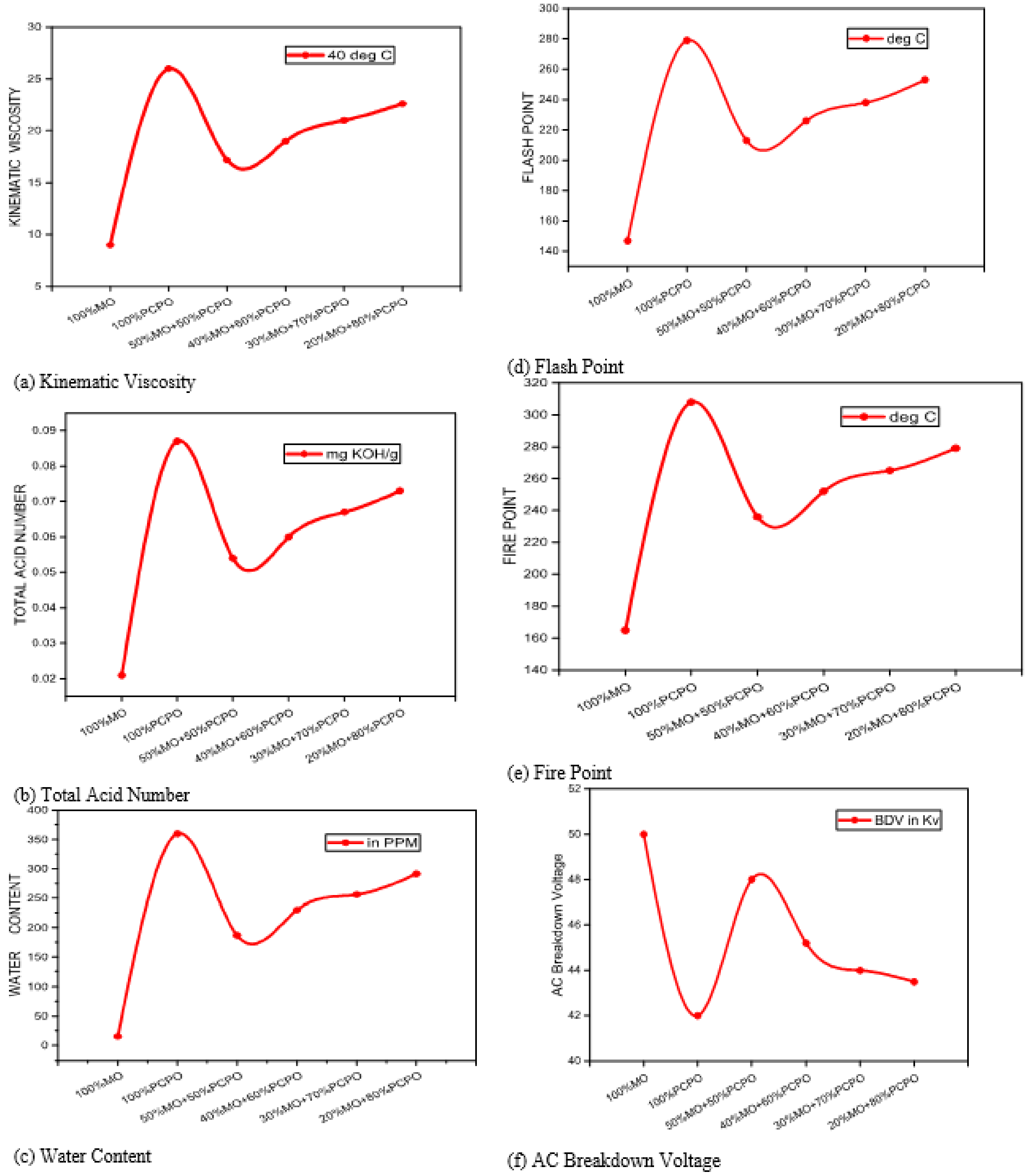

Figure 2. Various concentration of PCPO/MO mixtures

4. Conclusions

This present work shows that the Processed Ceiba Pentandra Oil, which is obtained from the two step chemical conditioning has provided the high heat transfer capacity through less kinematic viscosity and better safety with high flash and fire point. The dielectric strength has been improved by the Chemical conditioning and by the addition of suitable volume of alpha Tocopherol. From the overall observation, the Physicochemical and Electrical properties of Processed Ceiba Pentandra Oil have satisfied the IEEE Standard of C57.147-2018. This Processed Ceiba Pentandra oil has the potential to replace the mineral oil in high voltage electrical apparatus.

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