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Investigation and Analysis of Electro-physical Properties of Biodegradable Vegetable Oil for Insulation and Cooling Application in Transformers

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This paper focuses on the use of alternative insulating oil due to the lack of petroleum resources and concern about the environmental issues. For these purposes, a few vegetable oils available in Bangladesh are investigated for their electrical and physical properties. Vegetable oils are environmentally friendly because of their high biodegradability, low toxicity, high flash points and lower inflammability. This paper demonstrates the kinematic viscosities of sunflower oil, til oil and pithraj oil, which are found as 22.48 mm^2/s, 24.81 mm^2/s and 29.84 mm^2/s, respectively at 20°C. The electrical breakdown voltage obtained for sunflower oil, til oil and pithraj oil are found to be 18.53 kV, 16.17 kV and 15.03 kV, respectively, for a 2.5-mm gap between electrodes at 20°C. The statistical analysis of the breakdown voltage of the vegetable oils is conducted in this paper using 'R' software. Finally, the experimental results are compared with mineral oil, which is generally used in distribution transformers.

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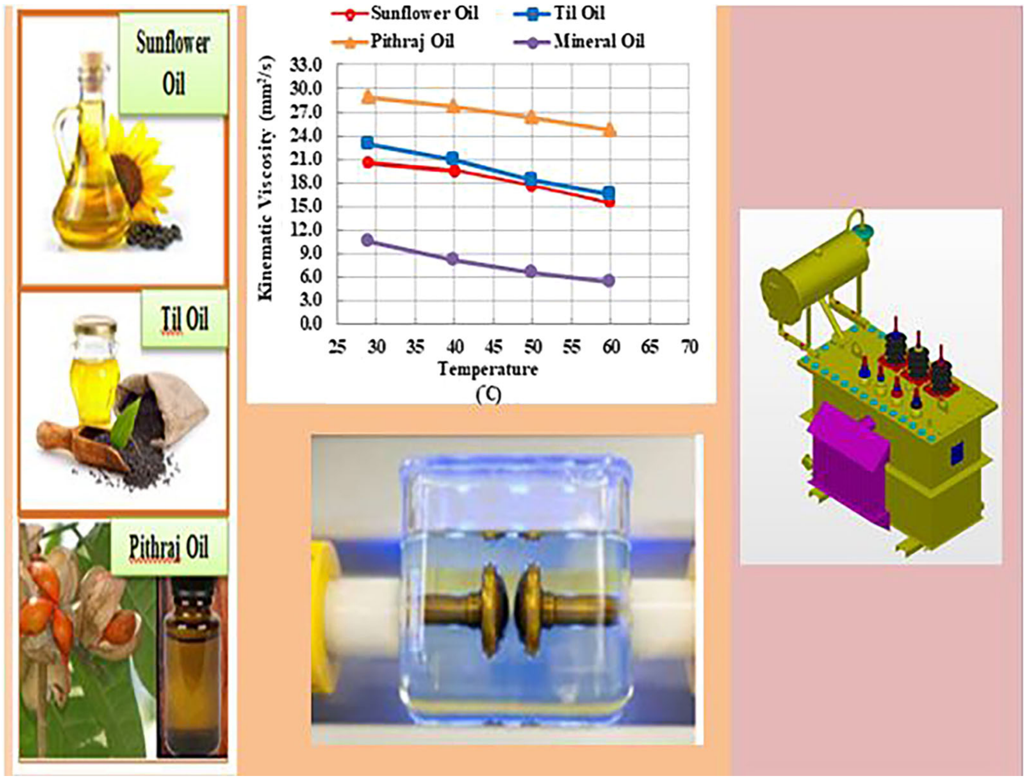
Graphic Abstract



Key words: Dielectric strength, kinematic viscosity, thermal conductivity, breakdown voltage, statistical analysis, normal distribution

INTRODUCTION

Fast industrialization and expanding power demand have coordinated to utilize mineral oils as insulation and a cooling apparatus in power system applications. However, owing to the shortage of mineral oil (MO) resources worldwide and having some different disadvantages, for example, non-biodegradability, non-sustainability and not being eco-accommodating, it is essential to discover a substitute solution for insulation purposes.[1–3] Vegetable oils are gathered from seeds from blossoms. The accessible vegetable oils in various nations of the world ought to be portrayed so as to utilize them in engineering application. Insulating fluids are characterized by their chemical properties, cost, wide accessibility and ageing stability. Vegetable oil has not only appropriate properties for utilization in high-voltage protection, it is also treated as a biological elective which is environmentally friendly, non-toxic and fire-resistant.[4]

For utilization of vegetable oil in insulation and cooling purposes, several vegetable oils have been demonstrates in previous research to have high dielectric strength and low viscosity.[5] Consequently, many researchers and industries are investigating vegetable oil as the perfect alternative for high-voltage engineering, especially for insulation and cooling.[6,7]

Electrical properties such as dielectric strength and specific resistance, and physical properties such as viscosity and thermal conductivity, are the significant properties of insulating oil for high-voltage applications. As diverse types of vegetable oils exist in industrial sectors of Bangladesh, it is a vital time to review the electrical and physical properties of those vegetable oils as substitutes for mineral oil. Various related inquiries have been conducted due to the the necessity of sustainable energy combined with environmental safety.[8,9]

In research performed on methyl ester waste vegetable oil as an auspicious substitute for mineral oil, the breakdown voltage and thermal conductivity were found to be greater than mineral oil at 48% and 33% respectively. However, viscosity measurement was not performed in this research.[10] Natural esters have higher viscosity which is adverse for cooling operation. Additionally, they have higher heat conductivity which is advantageous for power transformers.[11] A feasibility analysis of natural ester oil as a transformer oil has been performed in research and it was demonstrated that the electrical and chemical properties were satisfactory to meet the Malaysian standard.[12] Another study performed on biotran-35 and commercial mineral oil reported on the physical and electrical properties, i.e. viscosity, specific gravity, acidic value, dielectric strength, water content, dissipation factor, resistivity and pour point. Also, the study reported that the ageing effects and performance of vegetable oil were also found to be satisfactory.[13] Previous research demonstrates that groundnut and coconut oil are biodegradable, having a higher heat conductivity, although these oils cannot withstand extra-high voltages.[14] Palm oil and rice bran oil act as insulating liquids, as alternative of mineral oil in transformers; they are also biodegradable, environmentally friendly and easily available, as presented in previous research.[15]

Non-edible Pongamia pinnata oil is an unconventional insulating liquid, exhibits better dielectric strength, but for cooling purposes, it should be handled with care because of the high viscosity.[16] Olive oil and castor oil have demonstrated better performance as insulating fluids for high-voltage application at different ageing conditions. Methyl esters have been extracted from soybean, peanut, canola and cottonseed oil according to simple base-catalyzed trans-esterification, and, subsequently, it was refined to improve the electrical properties. Methyl esters have low viscosity and can be used as an insulating liquid.[17] However, no cost analysis of the vegetable oils has been conducted in regard to this issue. The suitability of vegetable oils is examined in different contemporary researches for use in transformer as an insulation and cooling medium.[18,19] Additionally, various research has been executed on a statistical approach regarding breakdown voltage analysis of liquid dielectrics used in high-voltage applications.[20–22] Therefore, in this paper, statistical techniques are applied for analyzing the dielectric breakdown voltage of vegetable and mineral oils. Furthermore, the electrical and physical properties along with thermal ageing are also analyzed.

Although, much analysis of vegetable oil as an insulating and cooling liquid has been performed, there has been no research conducted on the vegetable oils available in Bangladesh (i.e. sunflower oil, til oil and pithraj oil). Thus, it is imperative to evaluate the electro-physical properties of these oils to promote environmental sustainability. In this paper, three types of vegetable oils, namely, sunflower oil (SO), til oil (TO) and pithraj oil (PO) are investigated due to their availability and low cost.

This paper is organized as follows: The "Vegetable Oils" section illustrates the vegetable oils with their chemical composition and cost. The "Methodology" section describes the methodology of the analysis and investigation process for checking the suitability of these vegetable oils in transformers. The "Results and Discussion" section validates the results and discussion with statistical analysis, and the "Conclusion" concludes the work with future directions of related research.

Vegetable Oils

The scientific name of sunflower is Helianthus annuus, the seed of which can be used to produce oil. Sunflower oil is nonionic and nonvolatile in nature and it has less sensitivity to pH and ionic changes. Sunflower seeds encompass 48–52% of superior-quality edible oil and 40–50% of protein for feeding.[23] It is often used in food and cosmetic industry.

Til oil is extracted from the Sesamum indicum (sesame) seed which is an important oil seed crop in Bangladesh. Sesame seeds are rich in oil (40–45)%, calcium, phosphorous and oxalic acids. Seeds comprise 42–45% oil and 20% protein. The dielectric properties of sesame seeds are greatly affected by moisture content and bulk density. In Bangladesh, these types of seeds are very much available in almost all districts, thus making it the second highest oil manufacturing crop in the country.[24]

Pithraj oil (scientific name: *Aphanamixis polystachya*) is easily available in Bangladesh and is very inexpensive relative to the other oils.[25] Pithraj oil can play a vigorous role in the substitution of diesel fuel. It has a higher density than other oils used in this investigation.

Chemical Composition of Vegetable Oil

The vegetable oils used in this investigation and their chemical composition are given below. Tables I, II and III show the chemical composition of sunflower oil, til oil and pithraj oil, respectively.

Table I. Sunflower oil

Parameter	Percentage (%)
Palmitic acid (saturated)	5
Stearic acid (saturated)	6
Oleic acid	30
Linoleic acid	59

Table II. Til (sesame) oil

Parameter	Percentage (%)
Palmitic acid (saturated)	8
Stearic acid (saturated)	5
Oleic acid	39
Linoleic acid	41

Table III. Pithraj (Aphanamixis polystachya) oil

Parameter	Amount
Sulfur content, % (w/w)	8.091
Carbon residues % (w/w)	0.0593
Ash content % (w/w)	0.00255
Acid value, mg (KOH/g)	56.40

Table IV. Cost comparison of different insulating oils

Type of oil	Price/liter (BDT)
Transformer oil	300
Sunflower oil	200
Sesame oil	180
Pithraj oil	160

Cost Comparison

The cost of the three studied vegetable oils and mineral transformer oil is presented in Table IV below where the cost of transformer oil is higher than other vegetable oil. This cost is taken from the local markets of Bangladesh. On the other hand, owing to the availability of such vegetable oils in Bangladesh, the need to import mineral oil from abroad is being decreased. In this context, the vegetable oils mentioned earlier can be used as cost-effective insulation and cooling liquids for transformers.

METHODOLOGY

Available and cost-effective vegetable oil can be used instead of mineral oil for transformer applications due to limited mineral oil resources worldwide. In this context, investigation and analysis of the vegetable oils available in Bangladesh should be carried out; this will reduce costs and be environmentally friendly. From these perspectives, the authors selected three vegetable oils, namely, "sunflower oil", "til oil" and "pithraj oil." The oil used for insulation and cooling should possess good dielectric strength, excellent heat-transfer characteristics and must be thermally stable in a range of different operating conditions. All these properties are categorized as physical properties (viscosity, thermal conductivity, thermal resistance and so on), chemical properties (presence of water/moisture and impurities, acidity, chemical stability and so on) and electrical properties (dielectric strength, specific resistance, electrical conductivity and so on). In this investigation, determination of dielectric strength as an electrical property and viscosity tests as physical property are performed. Furthermore, mathematical modeling provides a way to determine the thermal conductivity and thermal resistance of different vegetable oils. Finally, the breakdown voltage with a varied gap between electrodes, and viscosity at different temperature are presented in this paper.

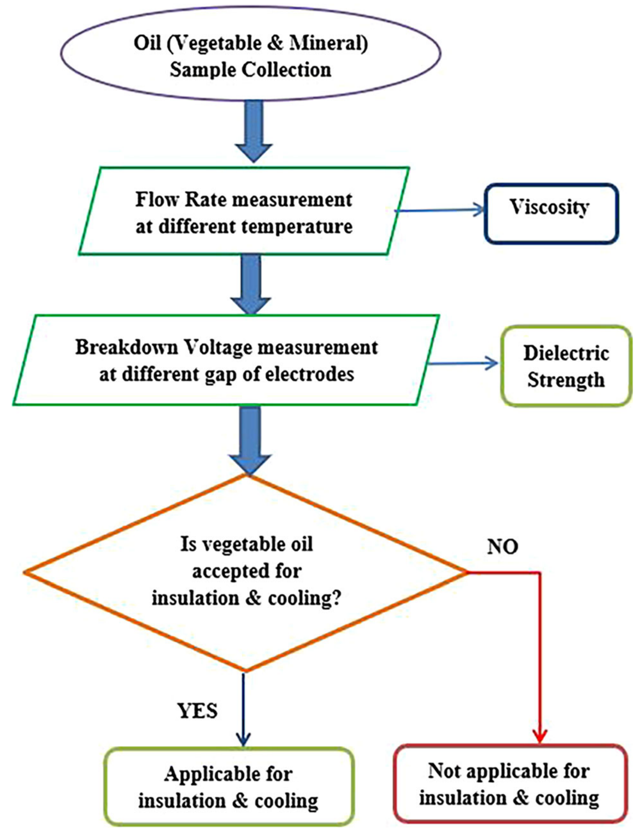


Fig. 1. Flow chart of the investigation process.

In order to explore the performance of vegetable oils as a new insulating and cooling liquid for high-voltage applications, several samples of the vegetable oils were collected from local markets of Gazipur district, Bangladesh. A mineral oil (transformer oil) sample collected from the high-voltage lab was also included for comparison. The viscosity of the vegetable oils (sunflower, til and pithraj) along with mineral oil (transformer oil) were measured using a viscosity measuring kit. This was done by measuring the flow rate of the oil by changing its temperature. By finding the viscosity, the relationship to thermal conductivity was elucidated. After that, the dielectric strength of vegetable oil and mineral (transformer) oil were measured. Testing of dielectric strength was conducted by changing the gap between the electrodes. For each oil sample, 10 readings were collected at each gap, and the mean value was determined. Finally, the obtained results were compared to mineral oil. A flow chart of the investigation process is presented in Fig. 1. Dielectric strength was measured in the High-Voltage Lab of the Electrical and Electronic Engineering Department, DUET, Gazipur, using a Foster OTS60SX oil dielectric tester, while the viscosity was measured in the Heat Transfer Lab of the Department of Mechanical Engineering, DUET, Gazipur, using a Saybolt universal viscometer. After that, statistical analysis of breakdown voltage was carried out to determine the mean value, standard deviation, histogram and probabilities (10% and 50%). The purpose of this statistical analysis is to determine whether the experimental data obey normal distribution law.

RESULTS AND DISCUSSION

The data obtained from the measurement of viscosity and dielectric strength of transformer oil and different vegetable oils are discussed in this section. To establish a vegetable oil as an insulating liquid, it is necessary to investigate the electrical and physical properties. Results of the experimental process indicate the studied vegetable oils are appropriate for insulation and cooling.

Kinematic Viscosity

The kinematic viscosity of a liquid indicates its heat transfer capacity, such that its cooling properties, in this case, vegetable oil, can be exposed. For a liquid, increased temperature leads to faster movement of molecules, which reveals that the density declines and the volume increases. Therefore, the density also affects the kinematic viscosity, as shown in Eq. 1.

$$\text{Kinematic viscosity}, v = \frac{\mu}{\rho}\,(\mathrm{m}^2/\mathrm{s}) \tag{1}$$

where v denotes kinematic viscosity (m^2/s), μ is the absolute viscosity (N s/m^2) and ρ is density (kg/m^3). Table V displays that increased oil temperature results in a decrease of the kinematic viscosity. The kinematic viscosity of different samples at 20°C is found to be within the range specified by the standard.[26] A lower value of thermal conductivity can be a cause of overheating in transformer application. Thus, a higher thermal conductivity is preferable for apparatus operated at high temperature. The kinematic viscosity can be used for analyzing the thermal conductivity of vegetable oils. The thermal conductivity can be obtained using Eq. :

$$\text{Thermal conductivity}, K = \frac{MV}{LT^2\theta} \tag{2}$$

where V = kinematic viscosity, M = mass of liquid vegetable oil, L = length/thickness of the tube where the liquid will flow, T = time to flow from the warmer edge to cooler edge in seconds, and θ = temperature between warmer and cooler edges. Equation 2 shows that if the temperature increases, the thermal conductivity decreased, and thus, thermal resistance will be increased.

Table V shows the kinematic viscosity for three vegetable oils including transformer mineral oil obtained from experimental investigation. Also, it shows that pithraj oil has a higher viscosity than the other oils. As the viscosity is related to the thermal conductivity, it thus plays a pivotal role in insulation and cooling applications. A lower viscosity results in a long transformer life due to increased cooling capacity. According to the standards ISO 3104 and ASTM D 445, the viscosity range should be about 3–16 mm^2/s for mineral oil and 16–37 mm^2/s for vegetable oil at 40°C.[26,27] In addition to this, the standard value of kinematic viscosity at 20°C should stand below 30 mm^2/s for a good-quality vegetable oil used as an insulation and cooling medium.[26,28] As observed in Fig. 2, at low temperature, the kinematic viscosity is high, whereas at high temperature, it is lower. At higher

Table V. Experimental data for measurement of the viscosity of transformer oil and different vegetable oils

Name of oil	Temperature (°C)	Kinematic viscosity at ambient temperature (mm^2/s)	Calculated kinematic viscosity (mm^2/s) (20°C)
Sunflower oil	29	20.57	22.48
	40	19.52	
	50	17.56	
	60	15.48	
Til oil	29	22.88	24.81
	40	20.84	
	50	18.25	
	60	16.58	
Pithraj oil	29	28.85	29.84
	40	27.73	
	50	26.30	
	60	24.79	
Mineral oil (transformer oil)	29	10.48	13.24
	40	8.12	
	50	6.57	
	60	5.38	

temperature, the oxidation rate increases and produces decomposition of the oils. If the kinematic viscosity is lower at higher temperature, it spreads the heat more quickly. Hence, thermal stability of the oils having a lower viscosity at higher temperature is necessary for transformer applications.[29,30]

The experimental observations indicate that sunflower oil, til oil and pithraj oil satisfy the requirements of kinematic viscosity for use as insulating liquids as per ISO 3104 and ASTM D 445 at 20°C and 40°C.

Figure 2 shows that the kinematic viscosity of vegetable oils decreases when temperature is increased. It is seen that all the vegetable oils undergo a decrease in kinematic viscosity with increasing temperature, which is essential for use as a cooling medium.

Dielectric Breakdown Strength

The breakdown voltages of the oil samples are determined experimentally for different electrode spacing ranging from 1.0 to 3.0 mm. This is done in order to compare the variation of breakdown voltage with changing gaps for different oils. Note that the minimum dielectric strength of the oil used in transformer should be 15 kV/mm at a 2.5-mm spark gap and 20°C for better performance.[26] Hence, in this paper, the breakdown voltage is analyzed for a 2.5-mm gap between electrodes to meet the IEC 60156 standard. Table VI displays that with the increase in the gap of the electrodes increase the breakdown voltage of the specified sample. All of these samples exhibit good dielectric strength within the standard limit range. The dielectric strength of pithraj oil is lower than til and sunflower oil, although it is within the range. This dielectric strength reveals that these oils can be utilized in transformers for insulation and cooling operations.

It is found that the mean breakdown voltage of the mineral oil, sunflower oil, til oil and pithraj oil are 56.60 kV, 42.50 kV, 38.76 kV and 36.50 kV, respectively, with a 2.5-mm gap between electrodes. The main function of these liquids is to provide electrical insulation along with the suppression of coronas and arcing. Figure 3 demonstrates variation of the dielectric breakdown voltage with a varied electrode gap. As in other studies, the breakdown voltage increases with increasing electrode gap.[31,32]

Statistical Analysis of Breakdown Voltage

The statistical analysis for breakdown voltage of different oil samples is done at a gap distance of 2.5 ± 0.05 mm. Statistical analysis is performed using 'R' software.[33] Each oil sample was tested 10 times to satisfy the number of tests required by statistical analysis. Note that the IEC 60156 standard requires only six measurements for each sample (IEC 60156:2018). Figure 4 shows the breakdown voltage scattering for different oils. All the oils, except mineral oil, exhibit uniform scattering of breakdown voltage.

In Fig. 5, the histograms of the breakdown voltages are presented for different oil samples. A histogram is usually used to present frequency distributions graphically. Vegetable oil shows

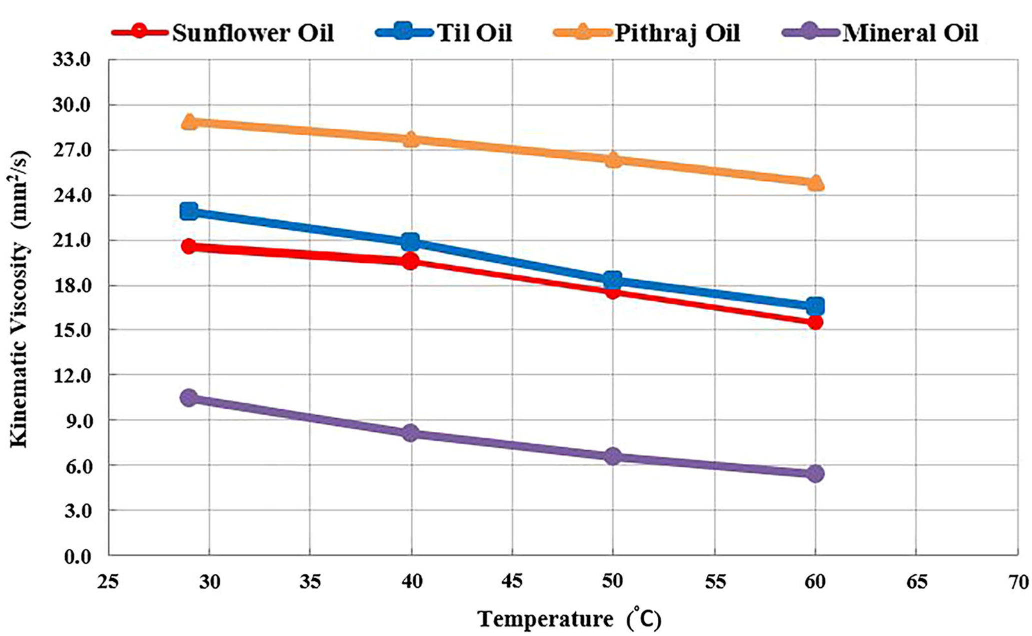


Fig. 2. Variation of kinematic viscosity with temperature of different vegetable oils.

Table VI. Dielectric strength of vegetable oils and transformer oil

Name of oil	Gap distance (mm)	Mean breakdown voltage (kV) at ambient temperature	Calculated dielectric strength at 20°C (kV/mm)
Sunflower oil	1.0	19.68	20.01
	1.5	28.82	19.52
	2.5	42.50	17.27
	3.0	47.40	16.05
Til oil	1.0	16.45	16.71
	1.5	24.28	16.45
	2.5	38.76	15.75
	3.0	43.60	14.77
Pithraj oil	1.0	15.23	15.47
	1.5	22.68	15.36
	2.5	36.50	14.98
	3.0	39.59	13.41
Mineral oil (transformer oil)	1.0	36.10	36.68
	1.5	46.40	31.42
	2.5	56.60	23.00
	3.0	58.75	19.90

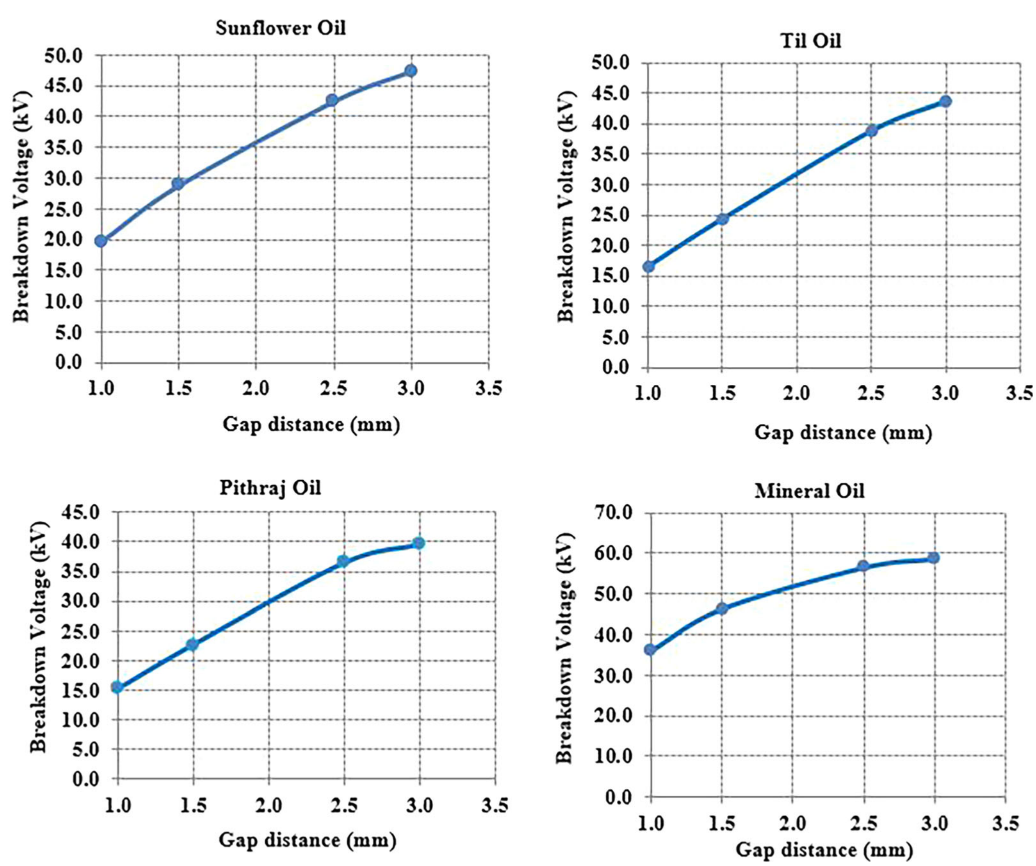


Fig. 3. Breakdown voltage versus gap between electrodes in different oils.

uniform breakdown voltage considering the standard deviation. However, mineral oil has higher standard deviation compared to other oils. This uniformity predicts that the use of vegetable oil would be better choice for high-voltage applications.

The skewness and kurtosis of normal distribution of breakdown voltage of tested oil samples are shown in Fig. 6a, whereas Fig. 6b presents the mean and standard deviations of breakdown voltage of the tested oils. In order to identify whether the distribution frequency is normal, skewness and kurtosis are determined. Skewness is an abstract quantity which indicates how data accumulated. The skewness will be positive if the longer tail is on the right side, whereas it will be negative is the longer tail is on the left side. In this analysis, it is found that SO shows the positive skewness, whereas other oils depict negative skewness.

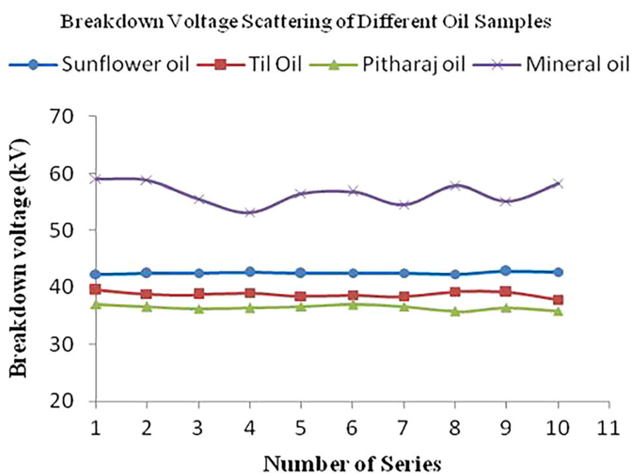


Fig. 4. Breakdown voltage scattering of SO, TO, PO and MO.

Kurtosis values obtained in this analysis are positive only for TO, while that for other oils remains negative. Positive kurtosis (leptokurtic) means that it has heavy tails, while negative kurtosis (platykurtic) has light tails compared to the normal distribution.

In order to identify that the data is following normal distribution or not, we applied the Shapiro–Wilk test to validate w and p values.[34] In this statistical analysis, normal distribution is considered with a significance level of the test, α of 5% ($\alpha = 0.05$). If the p value is greater than α, we may conclude that the null hypothesis is accepted. Table VII reveals the hypothesis test of conformity to normal distribution as indicated by the Shapiro–Wilk test. Table VII indicates that all the sample data are accepted.

The cumulative probability of the breakdown voltage of the oils is shown in Fig. 7. From Fig. 7, the probabilities U10% and U50%, which are the probabilities for breakdown voltages at 10% and 50% probability risk levels, are calculated in this statistical analysis. Calculation of breakdown voltage for low probability makes it possible to

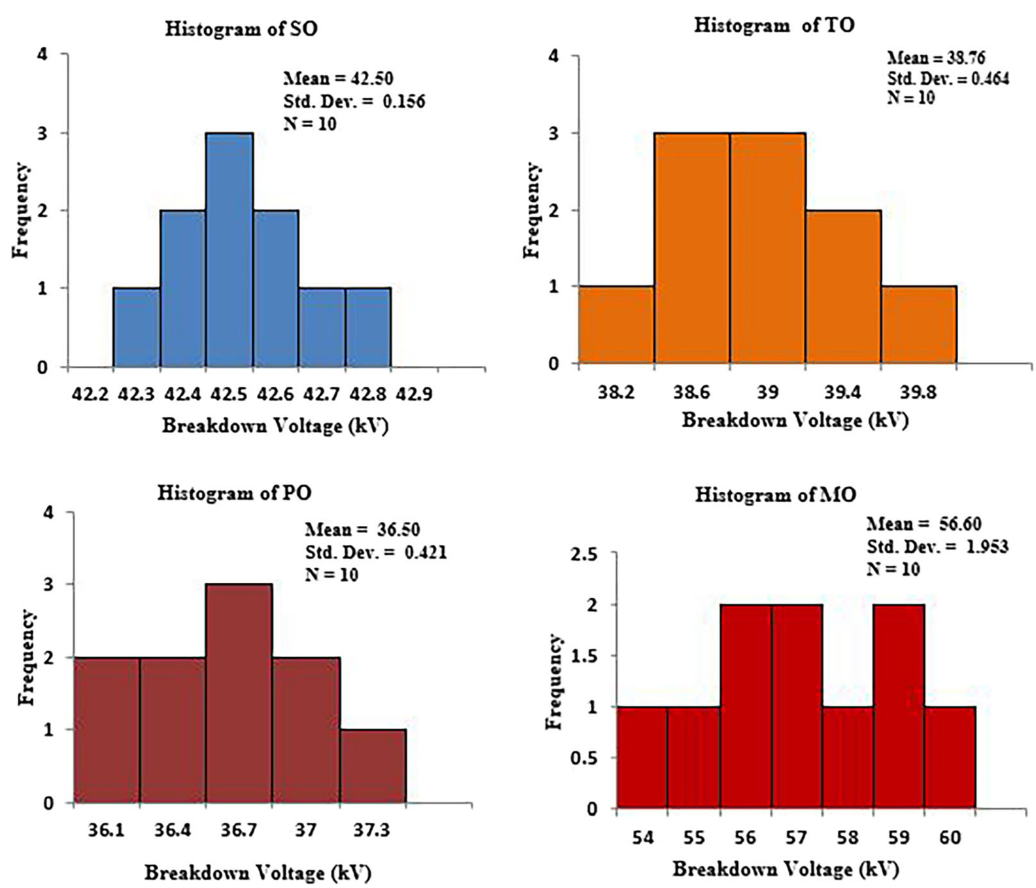


Fig. 5. Breakdown voltage histogram of SO, TO, PO and MO.

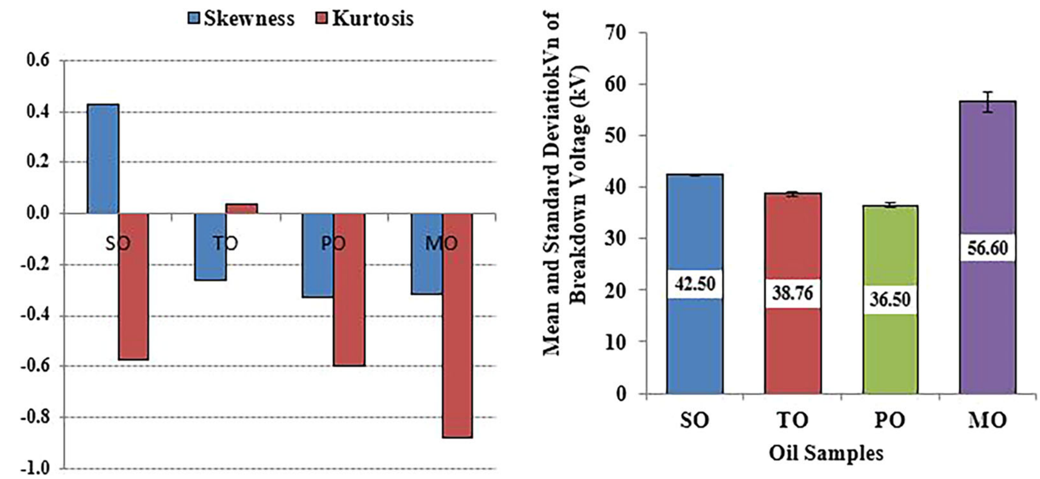


Fig. 6. (a) Skewness and kurtosis of normal distribution of breakdown voltage of tested oils. (b) Mean and standard deviation of breakdown voltage of tested oils.

Table VII. Shapiro–Wilk test for normal distribution

Sample	*w*	*p* value	Conformity to normal distribution
SO	0.97027	0.8934	Accepted
TO	0.98573	0.9884	Accepted
PO	0.96242	0.8131	Accepted
MO	0.95789	0.7615	Accepted

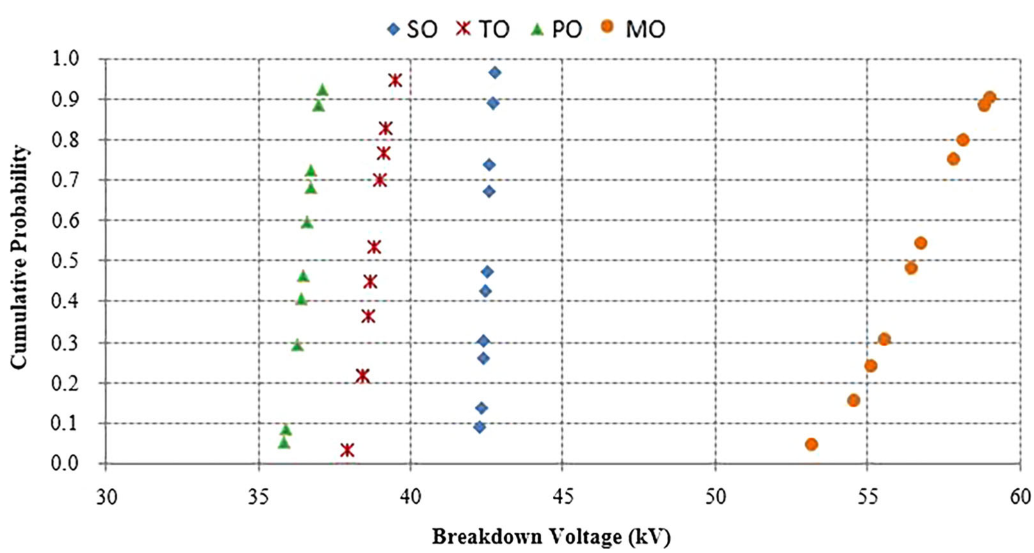


Fig. 7. Breakdown voltage probability curves of SO, TO, PO and MO.

determine a safety factor when designing electrical equipment. From Fig. 8, it is clear for SO that the breakdown voltage for 10% and 50% probability is higher than that of TO and PO.

As in other studies, we can make a conclusion, through the statistical analysis carried out, that the breakdown voltage of oils generally follows a normal distribution. However, the breakdown voltage obtained for vegetable oils is lower than that of mineral oil but higher than the minimum value required for high-voltage applications. As the mentioned vegetable oils exhibit suitable kinematic viscosity and dielectric strength as per experimental investigation, they would be appropriate insulation

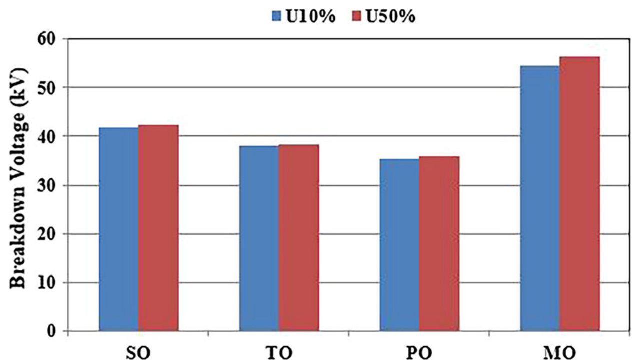


Fig. 8. Probability of breakdown voltage of SO, TO, PO and MO.

and cooling mediums in transformers. In addition, the biodegradability, low toxicity, low cost and availability makes these oils prominent alternatives for mineral oil used in transformer applications.

CONCLUSION

In this paper, kinematic viscosity and dielectric strength of vegetable oils are determined for use in high-voltage applications as a coolant and insulators. The results obtained from the investigation of vegetable oil are satisfactory and fall within the range of the standard limit. The kinematic viscosity of vegetable oils at 20°C is about 30 mm^2/s and within the required range, which indicates that it meets the criteria for use in transformers and any other high-voltage applications. Furthermore, the dielectric strength of vegetable oils at a 2.5-mm spark gap at 20°C is close to or greater than 15 kV/mm, which reveals that it is suitable for high-voltage application for insulation purposes in transformers. Moreover, statistical analysis shows that the breakdown voltage follows a normal distribution with a standard deviation within the limit. The breakdown voltages for 10% and 50% probability comply with the required value for high-voltage applications. As the vegetable oil samples are taken from the local market, there is a chance of having impurities and dissolved materials, which also affects the performance of vegetable oils. Therefore, it is suggested by the authors to first purify the vegetable oils taken from the markets by removing impurities and dissolved materials. In that case, the thermal conductivity and the dielectric breakdown strength will be improved further. Application of these liquids is possible in distribution transformers, circuit breakers, tap changers and capacitors at medium and high voltages and power range.

CONFLICT OF INTEREST

The authors affirm that there is no conflict of interest regarding publishing the paper.

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