Performance Analysis of Dielectric Properties of Blended Neem and Olive Oils using TOPSIS and Fuzzy TOPSIS Methods for Power Transformer

S. N. Deepa *‡, A. D. Srinivasan **, K. T. Veeramanju ***

*Assistant Professor, Department of E&EE, JSSSTU, SJCE, Mysuru, 570 006, Karnataka, India

** Professor, Department of E&EE, Dayananda Sagar College of Engineering, Bengaluru, Karnataka, India

***Former Professor, Department of E&EE, JSSSTU, SJCE, Mysuru, 570 006 Karnataka, India

(deepa.archak@jssstuniv.in, adsrinivasan@gmail.com, veeramanju.kalyan@gmail.com)

‡S. N. Deepa; Assistant Professor, Department of E&EE, JSSSTU, SJCE, Mysuru, 570 006, India,
Tel: +91 9449812401, deepa.archak@jssstuniv.in

Received: 20.06.2023 Accepted:12.08.2023

Abstract-A power transformer is the power distribution system's essential component that must be contractually monitored. The electricity supply has to be uninterrupted to keep a harmonious balance between consumer demand and supply, which depends on the reliability of the transformer. Also, liquid insulation that offers efficient cooling and insulation is very much crucial to the lifespan of the transformer. Conventionally, mineral oil is being used as a coolant and insulation medium for power transformers, which is a derivative of petroleum. The objective of this proposed investigation is to reduce reliance on fossil fuels that are increasingly scarce and to upsurge the use of oils derived from renewable sources. Thereby, to overcome the limitations of mineral oil, such as its poor biodegradability and weak flash and fire point, recent research has concentrated on natural ester liquid, environmentally acceptable insulating oil with commendable dielectric properties. In this paper, investigations were conducted to examine the functionality of olive oil, neem oil, and its blended samples at different proportions to replace mineral oil employed as liquid insulation in power transformers. The characteristics investigated are breakdown voltage, viscosity, moisture content, and oxidation stability of blended samples per IEC and ASTM standards. The multi-objective optimization tools such as TOPSIS and fuzzy TOPSIS were employed to optimize and choose the suitable natural ester for power transformers. Among the samples, NM50+OL50 presents a higher breakdown voltage of 59.96 kV with an induction time of 1.26 hrs and a viscosity of 42.92 cSt at room temperature. It was found that TOPSIS and Fuzzy TOPSIS methods have computational robustness in selecting NM50+OL50 as a suitable alternative to power transformers among the blended samples.

Keywords : Power transformer, liquid insulation, natural esters, blended oils, TOPSIS, fuzzy TOPSIS.

1. Introduction

The active pursuit of sustainable development involves efficient energy and resources, necessitating research into more environmentally friendly methods and sustainable materials [1]. The phenomenal growth in transformer manufacturing over the previous few decades has expanded the market for transformer liquid insulation. Since insulation issues are the leading cause of transformer failures, the durability of the insulation affects the transformer's lifespan; hence, insulating oil is crucial for power transformers to protect them against chemical attacks and internal short circuits and prevent sludge formation. Varied loading conditions, as well as external faults, could contribute to insulation deterioration. Hence electrical industry would suffer severe losses if this equipment failed[2-4]. All power transformers use liquid-insulating oils as a coolant to keep the transformer from overheating. These oils also offer electrical insulation, reduce corona and arching, and suppress corona [5]. An excellent insulation oil predominantly exhibits properties with a high breakdown voltage (dielectric strength), high chemical stability, a high degree of thermal stability, a low dielectric loss factor, a robust cooling medium, and cost-effectiveness [6, 7].

Conventionally, petroleum based mineral oils are being employed in power transformers. Even though mineral oils have good dielectric properties, they are non-biodegradable in nature, highly flammable, and hazardous to the environment [8]. Although its decomposition occurs very slowly, it can seriously contaminate soil and water sources in the event of equipment failure or spillage [9, 10]. Moreover, the availability of petroleum-based insulation oil is continuously reducing every year. With all the drawbacks, the energy crisis has led to a significant expansion in using renewable energy sources [11, 12]. Therefore, it is essential to find a solution to the problems mentioned in liquid dielectrics with ecologically friendly standards. In the last two decades, many researchers have focused on reliable, economical, and environmentally beneficial liquid insulation as a suitable alternative to conventional mineral oil. Oils derived from flowers, seeds, and vegetables are certainly biodegradable, and non-toxic, to both aquatic and terrestrial life

Natural ester-based transformer oil has several benefits over traditional transformer oil, including being more environmentally friendly, renewable, and non-toxic. Natural esters are becoming more acceptable as a substitute for mineral oil. Natural ester fluids comprise saturated fatty acids and single, double, and triple unsaturated fatty acids. Although saturated fatty acids have a high viscosity, but they are chemically stable. Triple unsaturated fatty acids have a lower viscosity, making them extremely unstable when oxidized. High concentrations of single unsaturated fatty acid-containing fluids are beneficial [13,14]. Natural esters develop hotspots in transformers due to their high viscosity, poor oxidation stability, and low pour points in their as-received state, which inhibits their capacity to dissipate heat [15, 16].

Even though studies on natural esters have produced promising results, the scope is there to analyze their aging and how stable they are in terms of their electrical qualities. Over the last years, few research has identified that combining natural esters enhanced their oxidative stability [17]. Thereby, considerable investigation of the long-term aging properties of vegetable oils and their blends should be conducted in electrical and chemical domains [18-20]. Also, due to the miscibility property of natural ester, blending two oils together could be one of the methods to improve the dielectric properties [21].

Hence, in this paper, based on selection criteria like availability, high monounsaturated fatty acid content, and good dielectric properties, neem oil, a non-edible oil, and yellow olive oil, an edible oil, have been selected to investigate their suitability to power transformers as liquid insulation. This investigation aims to develop an eco-friendly material for high-voltage applications.

Olive oil is a natural ester derived from olive trees' fruit (Olea Europea). Fruit grinding, malaxation of the resultant paste, and phase separation by centrifugation are the three key phases in its production [22]. Triglycerides comprise about 98-99% of the weight of olive oil (tricylglycerols consist of glycerol esterified by three fatty acids). Moreover, it includes free fatty acids, which vary according to how much triglyceride hydrolysis has occurred. Vegetable oils' dielectric and physiochemical characteristics are affected by these fatty acid's hydrocarbon chains and the degree of unsaturation [23].

Neem oil is a type of vegetable oil extracted from the fruit and seeds of the neem tree (Azadirachta indica). This evergreen tree is native to tropical areas of the Indian subcontinent. Neem oil may be extracted from the neem seed kernels in 25-45% yields. The seed kernels can be pressed (crushed) to get the oil, either by cold pressing or through a process including temperature controls between 40-50°C. It is mostly constituted of triglycerides and has a high concentration of triterpenoid chemicals, which cause the bitter flavor. It is hydrophobic by nature, but it is prepared with surfactants so that it may be emulsified in water for application purposes [24].

This investigation has evaluated neem oil, olive oil, and blended samples to analyse the compatibility of this selected natural ester as liquid insulation. Measurements of crucial characteristics, including breakdown voltage, moisture content analysis, oxidation stability, and viscosity of prepared samples, are performed as an element of suitability analysis. These characteristics are considered crucial regarding heat transmission capability, biodegradability, and insulating activity.

Several elements need to be considered throughout the evaluation process to choose the most ecological oil for the power transformer. In light of this, a sustainable selection procedure may be interpreted as a Multi-Criteria Decision-Making (MCDM) dilemma. The MCDM model generally includes the following steps [25]:

- Outlining the constraints and criteria.
- Setting the objective.
- Creating alternatives.
- Prioritize decision-making tools.
- Making a decision.

Further, the investigation analysis is extended to get the best oil out of all the prepared samples using the MCDM model, such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Fuzzy TOPSIS optimizing methods. Researchers are utilizing the TOPSIS and Fuzzy TOPSIS methods for optimizing the results because multiple parameters could be scrutinized altogether, and optimized results could be obtained immediately [26]. These methods are simple, unique properties can be considered and are used when conclusions cannot be drawn directly.

This paper contributes to the selection of a suitable alternative insulating liquid to replace conventional mineral oil. Experimental investigations and MCDM techniques were used to determine the suitable sample among the blended oils.

2. Materials and Experimental Methods

According to IEC and ASTM international standards, the dielectric properties for various blended proportions of oil samples are evaluated. These properties include breakdown voltage (BDV), moisture content analysis, oxidation stability, and viscosity measurement. All of the studies were conducted at standard room pressure and temperature.

2.1. Sample Preparation

In this work, neem and olive oil are selected for investigation and 500 ml of each sample is analyzed. Further, these oils are blended with each other in different proportions, and their dielectric properties are investigated. Five liters of each oil are collected from the local commercial market APMC, Mysuru, and stored in a glass container. With these oils as a primary sample, other samples are prepared by blending them with each other as in Table 1.

Samples are blended using the magnetic stirrer method. A magnetic pellet is dropped into the oil beaker and made to spin at the speed of 1500 rpm for about 10-15 mins and the prepared samples of blended neem oil and olive oil (NM100=1000ml neem oil, OL100=1000ml olive oil, NM50+OL50=500ml neem and 500ml olive oil, NM60+OL40 =600ml neem and 400ml olive oils, NM80+OL20=800ml neem and 200ml olive oils) are shown in Fig. 1.

Table 1. Samples and their proportions were taken for the study

Samples	Neem Oil (NM) (ml)	Olive Oil (OL) (ml)
NM100	1000	0
OL100	0	1000
NM50+OL50	500	500
NM60+OL40	600	400
NM80+OL20	800	200

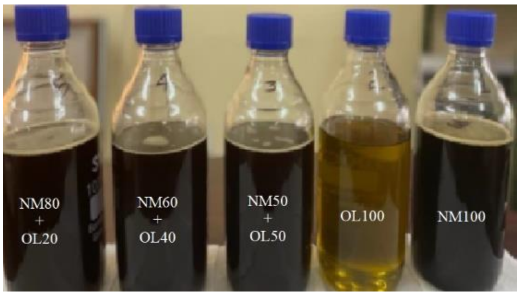


Fig. 1. Prepared samples for investigation.

2.2. Breakdown Voltage (BDV)

The effectiveness of using oil as perfect insulation depends on the BDV of the transformer's oil insulation. The potency of the oil affects its breakdown voltage. The breakdown voltage will drop significantly if impurities or moisture are trapped in the oil [27]. The IEC 60156 standard is followed while evaluating the breakdown voltage of oil insulation [28]. The experiment is performed with the prepared oil samples loaded into the oil test cup. The applied voltage to two spherical electrodes spaced apart by 2.5 mm in a test cup is adjusted by varying the variac. The experimental setup is illustrated in Fig. 2 and the breakdown voltage is recorded. For each sample, a total of fifteen readings have been taken to be taken into consideration to arrive at the average BDV.

Fig. 2. BDV test experimental setup.

2.3. Moisture Content Analysis

Excessive water content levels can eventually play a crucial role in transformer longevity as they influence the oil's dielectric characteristics and trigger transformer malfunction. Moisture is referred to as "the biggest adversary" of transformer insulation and can rapidly change within an operational transformer [29]. The two contributing factors to a rise in the amount of water content in transformer insulation are airway humidity and insulation deterioration. When oil is present in electrical equipment, the water travels together with the oil. This water might be in the form of dissolved water or a liquid that polar anti-aging products can absorb (bound water). Particles such as cellulose fibers have the ability to bind water.

Using a Volumetric Karl Fischer titrator outlined in ASTM Test Method D 1533 or IEC Method 60814, which can measure a wide range of moisture contents from a few ppm to 100% water, the prepared samples are examined for moisture content. This entails reducing an iodine-containing reagent using the coulometric titration method. The test necessitates the use of 10 cc of oil.

2.4. Oxidation Stability

Natural esters are bio-degradable in nature, although insulation oil spills are benefited by biodegradation, but in the presence of oxygen insulation oil should not degrade within the transformer tank. Compared to mineral oils, natural esters are more vulnerable to oxidation. Natural esters must be restrained from oxygen and moisture to perform at their highest potential. The easiest method to use the current emphasis is to hermetically seal against ambient air hermetically [30].

The oxidation stability of prepared samples is examined using Equipment—Rancimat 743, a PC-controlled measuring device for determining the oxidation stability of liquid dielectrics associated with an RS232 interface, as illustrated in Fig. 3.

Fig. 3. Rancimat 743 test set up to measure oxidation stability.

2.5. Viscosity

The oil's capacity to transfer heat indirectly influences its flow rate. The viscosity measures the oil's shear resistance to flow on the surface [26]. Oil viscosity tends to rise with age and oxidation, and temperature also has an impact. Conventional aging and oil oxidation have no effect on viscosity, but only in severe situations can corona release or oxidation impact viscosity. The viscosity of the oil influences heat transfers and, hence, the temperature rise of the equipment. Oil will flow more readily and efficiently; the process of heat transfer will be enhanced by a lower viscosity (dilute) value. Lower temperatures cause the oil's viscosity to increase (become thicker), and this is a crucial phase for the new transformer to run through since it prevents the oil from properly circulating and prevents overheating at some hot spots. The viscosity is measured using the Redwood Viscometer and following ASTM D445 standards [31]. The Redwood viscometer is illustrated in Fig. 4, where the amount of time needed for 50ml of oil sample to pass through the test orifice is monitored. Hence, the oil's viscosity is determined.

Fig. 4. Redwood viscometer to measure viscosity of oil.

3. Implementation of MCDM Methods

The Multiple criteria decision-making (MCDM) process is a way to make decisions that raises the level of overall satisfaction of the group members with the chosen course of action The benefit of MCGDM is that it makes use of popular wisdom [32]. In an MCDM problem, a group of decision makers is assembled to assist in ranking a limited number of options more logically by aggregating individual preferences while taking into account each decision maker's unique knowledge, experience, and competence within the decision variables [33, 34].

In the following subsections, this paper describes few MCDM techniques such as TOPSIS and Fuzzy TOPSIS methods which are undertaken to select the most suitable oil sample out of the prepared samples. The dielectric properties such as breakdown voltage, oxidation stability, moisture content, and viscosity are considered for evaluation. However, mathematical equations were incorporated to get the optimal outcome. The matrix will be taken into account; the rows represent the optimization choices, and the columns represent the test criterion.

3.1. Implementation of TOPSIS

TOPSIS (Technique for Ordering Preferences by Similarity to Ideal Solution) is a strategy for addressing multiple criterion decisions or challenges. The basic objective of TOPSIS method is to assess selections by comparing their distances to both the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS). The decision maker (DM) prefers PIS over NIS because it maximises benefits while minimising costs. NIS, on the other hand, maximises costs while minimising benefits, making it the least desired choice. The alternatives' nearness to PIS, a scalar criterion incorporating these two distance measures, is subsequently utilised to determine the ranking order. The classical TOPSIS technique relies on the presumption that the problem is described in the form of a decision matrix with comprehensive data, and that the assessment criteria, alternatives, criteria weights, and their resolution levels are defined precisely. In other words, it necessitates a well-structured decision [35]. The steps followed are described in the below section and flowchart is depicted in Fig. 5.

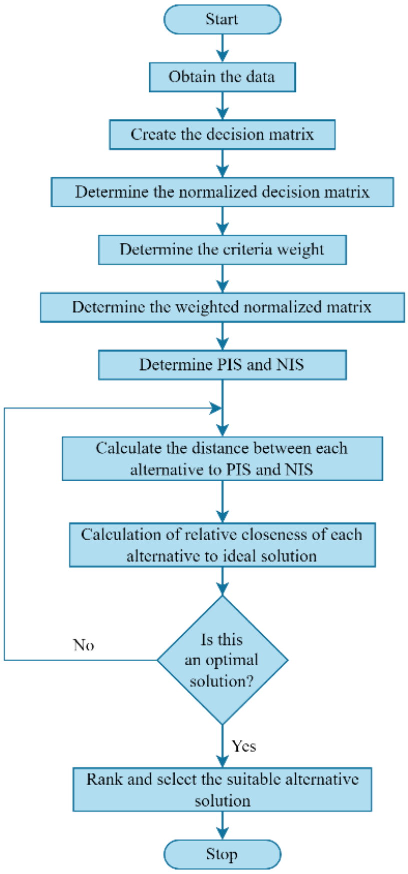


Fig. 5. The flow chart of TOPSIS method.

➢ *Normalization of decision matrix.*

The decision matrix (m x n) can be normalized using the following equation. Where $r_{ij}(\mathrm{x})$ is the normalized decision matrix.

$$r_{ij}(\mathrm{x}) = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} i = 1,2 \ldots, (m-1), m; \qquad (1)$$

$j = 1,2 \ldots, (n-1), n$

➢ *Calculation of weighted normalized decision matrix.*

The normalized matrix shall be multiplied with the weight of criteria to determine the weighted normalized decision matrix $v_{ij}(\mathrm{x})$.

$$v_{ij}(\mathrm{x}) = w_j r_{ij}(x) i = 1,2 \ldots, (m-1), m; \qquad (2)$$

$j = 1,2 \ldots, (n-1), n$

➢ Calculation of the PIS and NIS

PIS and NIS are determined using the Eq. (3) and (4). [35]

$A^+ = (v_1^+, v_2^+, \ldots, v_n^+)$ - positive alternative

$A^- = (v_1^-, v_2^-, \ldots, v_n^-)$ - negative alternative

So that,

$$v_j^+ = \{(max v_{ij}(x) | j \epsilon j_1), (min v_{ij}(x) | j \epsilon j_2)\} \qquad (3)$$

$i = 1,2 \ldots, (m-1), m$

$$v_j^- = \{(min v_{ij}(x) | j \epsilon j_1), (max v_{ij}(x) | j \epsilon j_2)\} \qquad (4)$$

$i = 1,2 \ldots, (m-1), m$

where $j_1$and j_2 are the negative and positive criteria.

➢ *Determination of distance from positive and negative ideal solutions.*

The TOPSIS technique assesses each alternative by accounting its closeness to the PIS and its distance from the NIS. As a result, the distances between every selection and PIS, NIS are calculated using Eq. (5) and (6). [35]

$$d_i^+ = \sqrt{\sum_{j=1}^{n} [v_{ij}(x) - v_j^+(x)]^2}, i = 1,2 \ldots, (m-1), m \quad (5)$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} [v_{ij}(x) - v_j^-(x)]^2}, i = 1,2 \ldots, (m-1), m \quad (6)$$

➢ *Calculation of relative closeness of alternatives to the ideal solution.*

Eq. (7) could be used to determine the extent to which each alternative pertains to the optimal solution. If the relative closeness degree is close to 1, the alternative is closer to PIS and farther away from NIS.

$$\mathrm{C}_i = \frac{d_i^-}{(d_i^+ + d_i^-)} \quad , \quad i = 1,2, \ldots, m \qquad (7)$$

Hench, by comparing C_i values, the ranking of alternative samples is determined.

3.2. Implementation of Fuzzy TOPSIS

It might be challenging for a decision-maker to rate an alternative's performance against the criteria being considered. The advantage of employing a fuzzy method is that fuzzy numbers, rather than precise numbers, may be used to determine the relative importance of attributes. The TOPSIS is stretched to the fuzzy environment used to rank the alternative in a fuzzy environment [36]. This approach is ideally suited for handling collective decision-making issues in uncertain situations. The flowchart is depicted in Fig. 6 and the steps involved in the Fuzzy TOPSIS method are as follows.

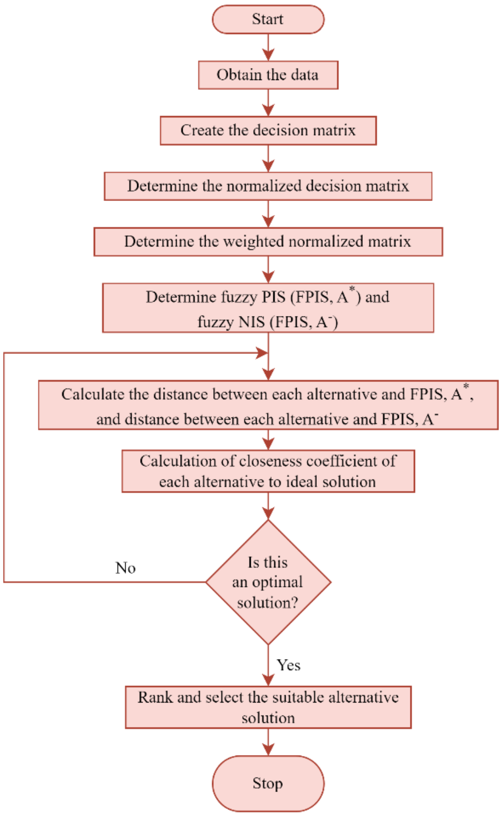


Fig. 6. The flow chart of the Fuzzy TOPSIS method.

➢ *Construction of decision matrix.*

➢ *Construct the normalized decision matrix.*

The following relationship could be employed to build a normalized decision matrix that considers the PIS and NIS:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right); \; c_j^* = max_i c_{ij} \text{ ; PIS (8)}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right); \; a_j^- = min_i a_{ij} \text{ ; NIS} \qquad (9)$$

➢ *Calculation of weighted normalized decision matrix.*

Considering the variable weights of each criterion, the weighted normalized decision matrix may be constructed by multiplying the weight of each criterion in the normalized fuzzy decision matrix by the following equation.

$$\tilde{v}_{ij} = \tilde{r}_{ij}.\widetilde{w}_{ij} \quad (10)$$

Where $\widetilde{w}_{ij}$ is the weight of criterion c_j

➢ *Calculation of fuzzy PIS (**FPIS, A***) and fuzzy NIS (**FNIS**, $\boldsymbol{A^-}$)*

FPIS and FNIS of the samples could be determined using following equations:

$$A^* = \{\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*\} = \left\{\left(\max_j v_{ij} \,|i \in B\right), \left(\min_j v_{ij} \,|i \in C\right)\right\} \quad (11)$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-\} = \left\{\left(\min_j v_{ij} \,|i \in B\right), \left(\max_j v_{ij} \,|i \in C\right)\right\} (12)$$

Where, $\tilde{v}_i^*$= maximum value of i for all alternatives, $\tilde{v}_1^-$= minimum value of i for all alternatives

B and C denotes the PIS and NIS respectively.

➢ *Calculation of distance between each alternative and FPIS$\boldsymbol{A^*}$and distance between each alternative and FNIS$\boldsymbol{A^-}$.*

The distance between each alternative and fuzzy PIS, the distance between each alternative and fuzzy NIS are determined as below:

$$S_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*) \quad \text{i=1,2,…,(m-1),m} \quad (13)$$

$$S_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \quad \text{i=1,2,…,(m-1),m} \quad (14)$$

Where, d = distance between two fuzzy numbers and can be calculated as follows, when two triangular fuzzy numbers (a_1, b_1, c_1) and (a_2, b_2, c_2) are given;

$$d_v(\widetilde{M}_1, \widetilde{M}_2) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]} \quad (15)$$

➢ *Calculation of closeness coefficient and ranking of alternatives.*

The below equation is employed to determine each alternative's closeness coefficient;

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (16)$$

The ranking of alternative samples is determined by comparing CC_i values.

4. Results and Discussion

Our study examines the feasibility of replacing commercial mineral oil with natural esters in its received and blended forms. The obtained results concerning its dielectric and thermal properties are analyzed to optimize the suitable proportions of the oil as transformer insulation.

4.1. *Breakdown Voltage (BDV)*

The critical feature in determining the dielectric strength of these oils is the measurement of the BDV employed for the insulation medium and cooling of power transformers. The high degree of interaction of natural esters due to breakdown that these oils have a higher affinity towards water than typical mineral oil, making them to be less sensitive to water content [36]. As described in the section on materials and methods, the BDV of prepared samples is evaluated in accordance with the prescribed standards and procedures. The BDV of investigated samples are summarized in Table 2 with the distribution map shown in Fig. 7.

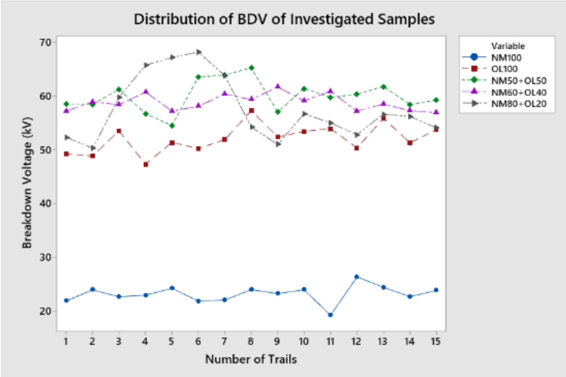


Fig. 7. Distribution of BDV of investigated samples.

The observations made after measuring breakdown voltage of prepared samples during the investigation are as follows:

➢ Breakdown voltage of blending sample NM50+OL50 is considerably high and found to be 59.98 kV at 50:50 proportion.

➢ Breakdown voltage of pure neem oil (NM100) is significantly lower with 23.12 kV compared to pure olive oil (OL100) with 52.02kV.

➢ The blended oil samples demonstrated a lower breakdown voltage for greater percentage concentrations of neem oil.

➢ As a result, the equal proportion of neem oil and olive oil composition elevated the dielectric strength of the blended oil in terms of breakdown voltage.

Table 2. BDV of investigated samples

Trail No.	Breakdown voltage (BDV) kV				
	NM 100	OL 100	NM50 +OL50	NM60 +OL40	NM80 +OL20
1	21.84	49.20	58.50	57.20	52.30
2	23.92	48.83	58.45	58.90	50.27
3	22.63	53.50	61.20	58.40	59.80
4	22.93	47.30	56.70	60.73	65.78
5	24.20	51.35	54.50	57.20	67.20
6	21.83	50.20	63.50	58.10	68.20
7	22.04	51.85	63.90	60.40	63.80
8	23.94	57.25	65.20	59.34	54.20
9	23.23	52.35	57.00	61.70	51.00
10	23.92	53.40	61.40	59.10	56.70
11	19.20	53.90	59.70	60.90	55.00
12	26.32	50.34	60.30	57.20	52.80
13	24.40	55.80	61.74	58.50	56.60
14	22.65	51.29	58.40	57.30	56.20
15	23.80	53.70	59.20	56.90	54.10
Average	**23.12**	**52.02**	**59.98**	**58.79**	**57.60**

When compared, the NM50+OL50 has a much higher breakdown voltage. This is primarily due to the oil mixture's high degree of water solubility, in which the hygroscopicity of natural esters encourages the adsorption of water from its surroundings. Esters' hygroscopicity is explained by the increased ability of the polar carboxyl group (-COOR) in the molecular chain structure to form hydrogen bonds [37-39]. As a result, the natural ester may dissolve substantially more water with a low relative water content, increasing the breakdown voltage of the oil-and-water combination.

Table 3 shows the median, standard deviation (SD), kurtosis, and skewness for the distributed trials of each investigated sample. A normally distributed data set has a skewness value of ‘0’ and a kurtosis value of ‘3’, with any change in these values indicating a divergence from the normal [40]. The skewness and kurtosis measure the symmetry of data and the number of extreme values. It is evident from Table 3 that skewness values for NM100 are negative, indicating the data is skewed left, and OL100, NM50+OL50, NM60+OL40, and NM80+OL20 are positive, stipulating the data to be skewed right.In all examined liquids, the standard deviation was essentially constant, except NM80+OL20. Also, the sample’s minimum and maximum breakdown voltage values were included.

Table 3. Statistical values of BDV of investigated samples

Variable	Mean	St Dev	Variance	Minimum	Median	Maximum	Skewness	Kurtosis
NM100	23.123	1.599	2.557	19.20	23.230	26.32	-0.57	2.18
OL100	52.017	2.669	7.125	47.30	51.850	57.25	0.19	-0.17
NM50+OL50	59.979	2.917	8.507	54.50	59.700	65.20	0.06	-0.34
NM60+OL40	58.791	1.553	2.413	56.900	58.500	61.70	0.51	-0.95
NM80+OL20	57.60	5.96	35.53	50.27	56.20	68.20	0.71	-0.85

4.1.1. Histogram of BDV of investigated samples

Fig. 8 shows the breakdown voltage frequency distributions for each of the examined oil samples represented by a histogram. The data distribution appears to be symmetrical around the mean value, which suggests that it is normal. The Anderson-Darling normality test was carried out to establish that the BDV of the examined samples is normally distributed.

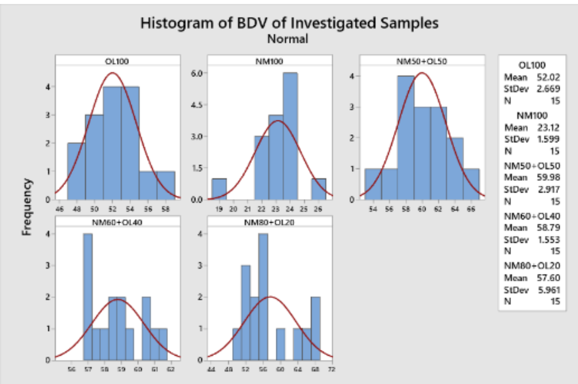


Fig. 8. Histogram of the breakdown voltage of investigated samples.

4.1.2. Normal probability distribution (NPD)

Figure 9shows the normal probability plots for all the examined oil samples with mean, standard deviation, number of samples (N), p-values, and Anderson Darling (AD). The solid lines reflect BDV data estimated by the normal distribution, which is subsequently used to calculate the probability of liquid insulation failure. Table 4 shows the propriety values of hypothesis conformity test to NPD of investigated samples.

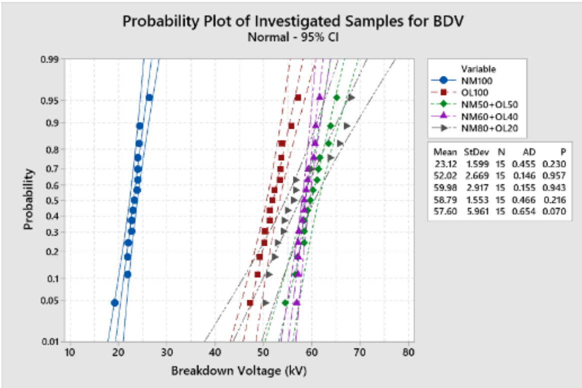


Fig. 9. Normal probability plot of examined samples for BDV.

Table 4. Hypothesis Conformity Test to NPD

Oil Samples	AD	p - Value	Conformity of NPD
NM100	0.455	0.230	Accepted
OL100	0.146	0.957	Accepted
NM50+OL50	0.155	0.943	Accepted
NM60+OL40	0.466	0.216	Accepted
NM80+OL20	0.654	0.070	Accepted

This result clearly validates the contention that BDVs are uniformly distributed throughout all liquid samples. NM60+OL40, NM50+OL50, and NM80+OL20 had relatively similar breakdown voltage characteristics in the 0.6948 probability region. The BDV values for several samples with low and high probability indicated a notable divergence from a perfectly normal distribution.

4.1.3. Weibull probability distribution (WPD)

The values of BDV for the blended samples of neem oil and olive oil are investigated using the Anderson-Darling test. They evidently fell within the permitted range. The hypothesis conformity test to the Weibull distribution accepted for investigated samples is shown in Table 5.

Figure 10 depicts the probability curves emerging from the Weibull distribution with the number of samples (N), Anderson–Darling (AD), shape, scale, and p-values. NM60+OL40, NM50+OL50, and NM80+OL20 had relatively similar breakdown voltage characteristics in the 0.6948 probability region. However, the p-value of NM80+OL20 is 0.024, which indicates that breakdown voltage is statistically significant in this region. The AD of NM50+OL50 is 0.306, which indicates that the distribution of breakdown voltage is best.

Table 5. Hypothesis Conformity Test to WPD

Oil Samples	AD	p-Value	Conformity of WPD
NM100	0.487	0.214	Accepted
OL100	0.315	> 0.250	Accepted
NM50+OL50	0.306	> 0.250	Accepted
NM60+OL40	0.623	0.092	Accepted
NM80+OL20	0.846	0.024	Accepted

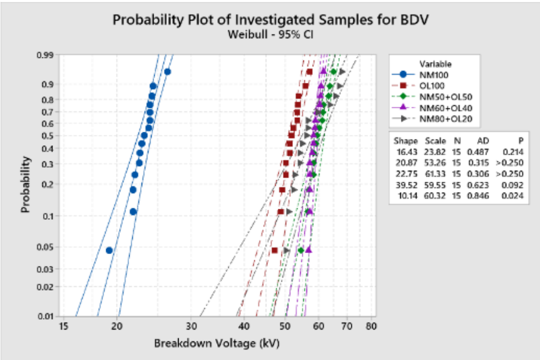


Fig. 10. Weibull probability plot ofexamined samples for BDV.

4.2. Moisture Content

The moisture content in the investigated samples is depicted in Fig. 11 and is recorded in Table 6. NM100 exhibits the highest value of 1530 ppm moisture content, whereas OL100 exhibits the lowest value of 777.64 ppm. This is because of the reason that olive oil has more fatty acids than neem oil [41].

The hydrolysis process occurs because of the presence of moisture content and enzyme activity. On average, neem oil has more moisture than olive oil. Neem oil's higher moisture content is most likely caused by the presence of water, which accelerates hydrolysis and shortens the oil's life span [42, 43]. In contrast, olive oil's reduced moisture content is caused by ligase activity.

From the experimental results, it is evident that NM100 has the highest moisture content, which breaks down the molecular bonds of the insulating oil and hinders the suitability of insulating liquid due to degradation. However, when blended with the olive oil, the characteristics of olive oil lowered the moisture content of the neem oil, and hence, the blended samples are more competent as transformer oil. Among the blended samples, NM60+OL40 has the least moisture content of 910.42 ppm, which is suitable for power transformers.

Table 6. Propriety values of moisture content present in the samples

Samples	Moisture content (ppm)
NM100	1530.026
OL100	777.646
NM50+OL50	1009.51
NM60+OL40	910.416
NM80+OL20	972.33

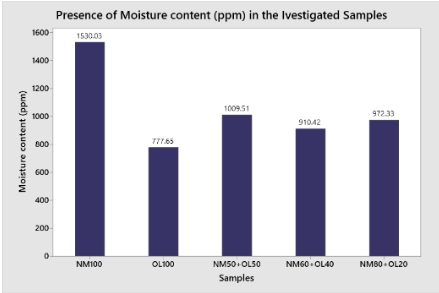


Fig. 11. Presence of moisture content in the samples.

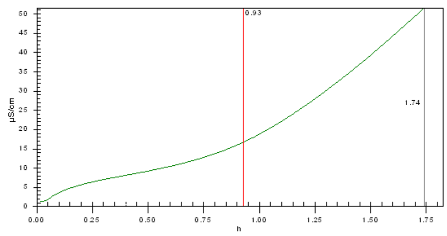
4.3. Oxidation Stability

Free radicals formed due to the interaction between the insulation oil and oxygen which accelerate the chemical reaction of oxidation. Catalysts such as water, copper, and acids may expedite the process. Water and acids could be produced during oil oxidation, speeding up the aging process for the oil and the paper. Furthermore, sludge and other insoluble substances may build up and obstruct the oil duct and extreme conditions might disrupt the oil flow, reducing the effectiveness of transformer cooling.

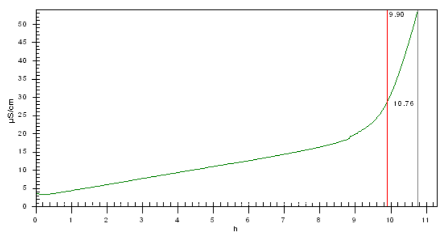
Hence, the study of oxidative stability is of prime importance, conducted at a temperature of 110 °C. The determined induction times for investigated samples are tabulated in Table 7 and illustrated in Fig. 12.

Table 7. Oxidation stability of investigated samples

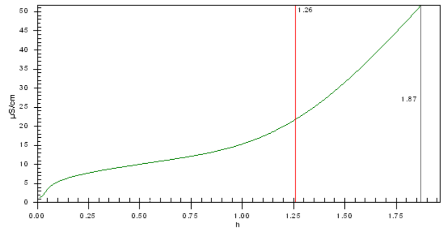
Samples	Induction time in hours
NM100	0.93
OL100	9.90
NM50+OL50	1.26
NM60+OL40	0.14
NM80+OL20	0.76



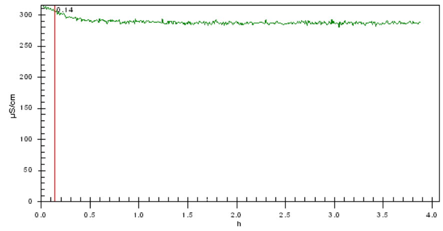
(a) NM100



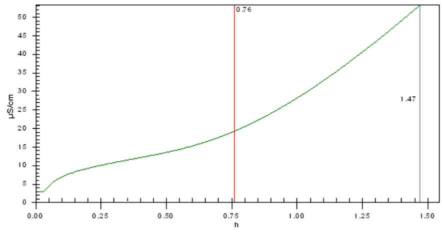
(b) OL100



(c) NM50+OL50



(d) NM60+OL40



(e) NM80+OL20

Fig. 12. Induction time of investigated samples for oxidation stability.

It was evident that, the induction time for OL100 was high with 9.9 hours indicating oxidatively stable. Among the blended samples, NM50+OL50 shows a better induction time of 1.26 hours. NM60+OL40 gets oxidized so quickly with an induction time of 0.14 hours, stipulating that it is not the better choice for power transformers.

4.4. Viscosity

The viscosity of the investigated samples is measured at room temperature of 26°C and shown in Fig. 13. It was noted that NM100 possesses the highest viscosity of 50.11 cSt, whereas OL100 has the least value of 41.19 cSt at 90°C, which is more favorable. Among the blended samples, NM60+OL40 is quite suitable for power transformers with a viscosity of 42.43 cSt.

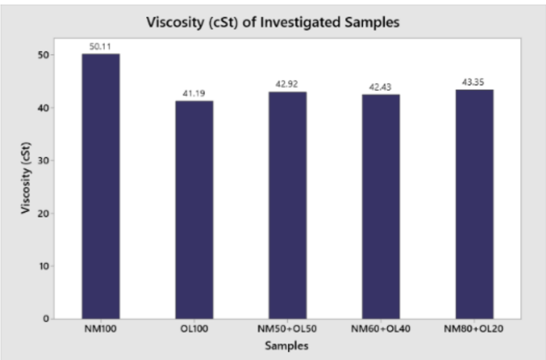


Fig. 13. Viscosity of investigated samples.

5. Ranking of Oils Using TOPSIS and Fuzzy TOPSIS Methods

The implementation of TOPSIS and Fuzzy TOPSIS section covers the basics of the equations implemented to optimize the objectives outlined. The initial process is to create a decision matrix by selecting the augmented (the greater, the better) and restricted test (smaller, the better) conditions. This decision matrix shall include the results of several tests carried out on a specific sample. When the decision matrix is established, as shown in Table 8, the parameters must be normalized with the test parameters considered using the aforementioned equations.

5.1. Ranking of Oils by TOPSIS Methods

This study has 4 criteria and 5 alternatives that are ranked based on the TOPSIS technique. The individual element is normalized using Eq. (1) for the decision matrix shown in Table 8, and the final normalized decision matrix for the TOPSIS analysis is illustrated in Table 9.

Table 8. Decision matrix for TOPSIS method

Samples	BDV (kV)	Moisture Content (ppm)	Oxidation Stability	Viscosity (cSt)
NM100	23.12	1530.03	0.93	50.11
OL100	52.02	777.65	9.90	41.19
NM50+OL50	59.98	1009.51	1.26	42.92
NM60+OL40	58.79	910.42	0.14	42.43
NM80+OL20	57.60	972.33	0.76	43.35

Table 9. Normalized decision matrix for TOPSIS method

Samples	BDV (kV)	Moisture Content (ppm)	Oxidation Stability	Viscosity (cSt)
NM100	0.198	0.639	0.093	0.508
OL100	0.446	0.325	0.985	0.418
NM50+OL50	0.514	0.421	0.125	0.435
NM60+OL40	0.504	0.38	0.014	0.43
NM80+OL20	0.494	0.406	0.076	0.439

The weighted normalized decision matrix was determined using Eq. (2), which is tabulated in Table 10. Then, positive and negative ideal solutions are calculated using Eq. (3) (4), and distance from them is determined using Eq. (5) (6), which are shown in Table 11 and Table 12, respectively.

Table 10. Weighted normalized decision matrix for TOPSIS method

Samples	BDV (kV)	Moisture Content (ppm)	Oxidation Stability	Viscosity (cSt)
NM100	0.05	0.16	0.023	0.127
OL100	0.111	0.081	0.246	0.104
NM50+OL50	0.129	0.105	0.031	0.109
NM60+OL40	0.126	0.095	0.003	0.108
NM80+OL20	0.123	0.101	0.019	0.11

Table 11. PIS and NIS values

Properties	PIS	NIS
BDV (kV)	0.129	0.05
Moisture Content (ppm)	0.081	0.16
Oxidation Stability	0.246	0.003
Viscosity (cSt)	0.104	0.127

Table 12. Distance to PIS and NIS

Samples	Distance to PIS	Distance to NIS
NM100	0.25	0.02
OL100	0.017	0.263
NM50+OL50	0.216	0.101
NM60+OL40	0.243	0.102
NM80+OL20	0.228	0.097

Table 13 tabulates the relative closeness degree of each alternative to the ideal solution and its ranking. It was evident that OL100 ranks first with regard to the selected criteria, but among the blended samples, NM50+OL50 was found to be a more suitable insulation oil for power transformers as per TOPSIS analysis.

Table 13. The $C_i$value and ranking

Samples	C_i	Rank
NM100	0.073	5
OL100	0.939	1
NM50+OL50	0.319	2
NM60+OL40	0.296	4
NM80+OL20	0.298	3

5.2. Ranking of Oils by Fuzzy TOPSIS Methods

The prevalent approach for multi-criteria decision-making (MCDM) used to rank the alternative in a fuzzy environment can be calledfuzzy TOPSIS. This study uses the FUZZY TOPSIS approach to rank 4 criteria and 5 alternatives. The fuzzy scale utilized in the model can be seen in Table 14.

Table 14. Fuzzy Scale used for Fuzzy TOPSIS method

Code	Linguistic terms for fuzzy scale	L	M	U
1	Very low	1	1	3
2	Low	1	3	5
3	Medium	3	5	7
4	High	5	7	9
5	Very high	7	9	9

Based on PIS and NIS, a normalized decision matrix can be determined using Eq. (8) (9) as shown in Table 15. And weighted normalized decision matrix is calculated using Eq. (10) as depicted in Table 16.

Table 15. A normalized decision matrix

Sample	BDV (kV)	Moisture Content (ppm)	Oxidation Stability	Viscosity (cSt)
NM100	(0.111,0.111,0.333)	(0.333,1.000,1.000)	(0.333,0.556,0.778)	(0.333,1.000,1.000)
OL100	(0.111,0.333,0.556)	(0.111,0.111,0.143)	(0.778,1.000,1.000)	(0.111,0.111,0.143)
NM50+OL50	(0.778,1.000,1.000)	(0.200,0.333,1.000)	(0.556,0.778,1.000)	(0.143,0.200,0.333)
NM60+OL40	(0.556,0.778,1.000)	(0.111,0.143,0.200)	(0.111,0.111,0.333)	(0.111,0.143,0.200)
NM80+OL20	(0.333,0.556,0.778)	(0.143,0.200,0.333)	(0.111,0.333,0.556)	(0.200,0.333,1.000)

Table 16. The weighted normalized decision matrix

Samples	BDV	Moisture Content	Oxidation Stability	Viscosity
NM100	0.028,0.0) (28,0.083	0.083,0.2) (50,0.250	0.083,0.1) (39,0.194	0.083,0.2) (50,0.250
OL100	0.028,0.0) (83,0.139	0.028,0.0) (28,0.036	0.194,0.2) (50,0.250	0.028,0.0) (28,0.036
NM50+ OL50	0.194,0.2) (50,0.250	0.050,0.0) (83,0.250	0.139,0.1) (94,0.250	0.036,0.0) (50,0.083
NM60+ OL40	0.139,0.1) (94,0.250	0.028,0.0) (36,0.050	0.028,0.0) (28,0.083	0.028,0.0) (36,0.050
NM80+ OL20	0.083,0.1) (39,0.194	0.036,0.0) (50,0.083	0.028,0.0) (83,0.139	0.050,0.0) (83,0.250

The positive and negative ideal solutions are calculated using Eq. (11) (12) and are shown in Table 17.

Table 17. PIS and NIS of fuzzy TOPSIS method

Properties	PIS	NIS
BDV	(0.194,0.250,0.250)	(0.028,0.028,0.083)
Moisture Content	(0.028,0.028,0.036)	(0.083,0.250,0.250)
Oxidation Stability	(0.194,0.250,0.250)	(0.028,0.028,0.083)
Viscosity	(0.028,0.028,0.036)	(0.083,0.250,0.250)

Table 18 shows the distance from positive and negative ideal solutions calculated using Eq. (15). The closeness coefficient of each alternative can be determined using Eq. (16) and is tabulated as follows.

Table 18. Distance from PIS and NIS with $CC_i$and ranking of alternative samples

Samples	Distance from PIS	Distance from NIS	CC_i	Rank
NM100	0.645	0.096	0.13	5
OL100	0.15	0.595	0.798	1
NM50+OL50	0.204	0.588	0.742	2
NM60+OL40	0.251	0.495	0.663	3
NM80+OL20	0.406	0.393	0.492	4

It was evident from Table 18 that OL100 ranks first with respect to the selected criteria, but among the blended samples, NM50+OL50 was found to be a more suitable insulation oil for power transformers as per Fuzzy TOPSIS analysis.

Figure 14 shows the ranking of investigated samples as suitable liquid insulation oil for power transformers using

TOPSIS and Fuzzy TOPSIS methods indicating $C_i$and CC_ivalues.

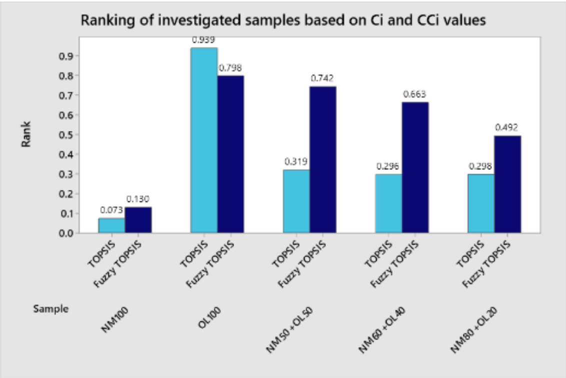


Fig. 14. Ranking of investigated samples based on $C_i$and CC_ivalues.

6. Comparison of Obtained Results with Acceptable Standards

The measured values of investigated parameters are compared with the acceptable standards and are tabulated in Table 19.

Table 19. Comparison of obtained results with acceptable standards

Sl .No.	Electrical Property	Mineral Oil	Natural Ester	NM100	OL100	NM50+OL50	NM60+OL40	NM80+OL20
1	Breakdown Voltage (KV) IEC60156	45-55	80-85	23.12	52.02	59.98	58.79	57.60
2	Viscosity Cst@40°C IEC 60814	3-16	16-50	41.43	41.18	42.92	42.43	43.34
3	Oxidation stability (Induction time hrs) ISO6886	160	-	0.93	9.90	1.26	0.14	0.76
4	Moisture content(ppm) IEC60814	-	-	1530	777.6	1009.5	910.4	972.33

7. Conclusion

The insulation and cooling system will serve as the primary components for the power transformers. This paper aims to accelerate the replacement of conventional mineral oils with natural ester-based and blended insulating oils. This paper analyzed the BDV of insulation liquid, physical characteristics such as moisture content, oxidation stability, and viscosity of neem oil, olive oil, and its blended samples. It was evident that the breakdown voltage of blended samples was considerably higher than base oils such as neem and olive oil. Also, the Normal and Weibull probability distribution hypothesis test accepted that breakdown voltages for all investigated samples are regularly distributed. Among the blending samples, the BDV of NM50+OL50 was highest and found to be 59.98 kV with an induction time of 1.26 hours, moisture content of 1009.51 ppm, and viscosity of 42.92 cSt, which are within acceptable limits of IEC and ASTM standards for liquid dielectrics. As a result, NM50+OL50 has been determined to be the most effective blend for transformer insulation liquid with better physical and dielectric properties out of all the prepared samples. The characteristics of olive oil lowered the moisture content of the neem oil in the blended samples. Upon successfully implementing the TOPSIS and Fuzzy TOPSIS method of the MCDM technique with various parameters, NM50+OL50 was inferred to be the better substitute in the entire test among the blended samples, and the optimized result ranked it first. Future research has the potential to test for the parameters considered with antioxidants added to enhance the dielectric properties. Moreover, the influence of moisture and oxidation stability value can be investigated.

References

[1] M. Herrero, & E. Ibanez, "Green processes and sustainability: An overview on the extraction of high added-value products from sea weeds and microalgae", The Journal of Supercritical Fluids, 96, 211-216, 2015.

[2] J. Penfield, M. Holland, "Machine Learning Based Online Monitoring of Step-Up Transformer Assets in Electrical Generating Stations", In 2021 9th International Conference on Smart Grid (icSmartGrid) pp. 32-36. IEEE, June 2021.

[3] S. Yurekten, A. Kara and K. Mardikyan, "Energy efficient green transformer manufacturing with amorphous cores", International Conference on Renewable Energy Research and Applications (ICRERA), Madrid, Spain, pp. 534-536, 2013.

[4] V. Nurmanova, Y. Akhmetov, M. Lu, M. Bagheri, T. Phung, "Transformer winding modelling to study the effect of inter-disk faults on frequency response signature", 8th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 540-544, IEEE. 2019.

[5] D. C. Abeysundara, C. Weerakoon, J. R. Lucas, K. A. I. Gunatunga, K.C. Obadage "Coconut oil as an alternative to transformer oil", 8th Annual Conference of the IEE, ERU Symposium, Sri Lanka, 2001.

[6] D. H. Fontes, G. Ribatski, E. P. B. Filho, "Experimental evaluation of thermal conductivity, viscosity and breakdown voltage AC of nanofluids of carbon nanotubes and diamond in transformer oil", Diamond and Related Materials, Volume 58, Pages 115-121, ISSN 0925-9635, 2015.

[7] F. S. Suwarno, S. Ichwan and I. Luthfi, "Study on the characteristics of palm oil and its derivatives as liquid insulating materials", Proceedings of the 7th

International Conf. on Properties and Applications of Dielectric Materials, Nagoya, vol.2 ,pp. 495-498, 2003.

[8] G. Romadhona, K. K. Wibowo, R. Royan, “Study of extra virgin olive oil as liquid insulation in transformer” IOP Conference Series: Earth and Environmental Science. Vol. 700. pp. 012030, March 2021.

[9] Y. Xu, S. Qian, Q. Liu and Z. D. Wang, "Oxidation stability assessment of a vegetable transformer oil under thermal aging," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 21, no. 2, pp. 683-692, April 2014.

[10] T. Suzuki, A. Kanetani, R. Oba and T. Kano, “Consideration on the relationship between dielectric breakdown voltage and water content in fatty acid esters” IEEE Int. Conf. Dielectric. Liq. pp. 1-4, 2011.

[11] A. El Shafei, S. Ozdemir, N. Altin, G. Jean-Pierre, A. Nasiri, “A complete design of a high frequency medium voltage multi-port transformer”, In 2019 8th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 761-766. IEEE, November 2019.

[12] F. Ayadi, I. Colak, I. Garip, H. I. Bulbul, “Impacts of renewable energy resources in smartgrid”, 8th International Conference on Smart Grid (icSmartGrid) pp. 183-188, IEEE. June 2020.

[13] R. Eberhardt, H. M. Muhr, W. Lick, F. Baumann, G. Pukel, “Comparison of alternative insulating fluids”, In Annual Report Conference on Electrical Insulation Dielectric Phenomena, pp. 591–593, 2008.

[14] L. Hosier, A. Guushaa, E. W. Westenbrink, C. Rogers, A. S. Vaughan and S. G Swingler., “Aging of biodegradable oils and assessment of their suitability for high voltage applications”, IEEE Trans. Dielectric. Electrical Insululation, Vol. 18, No. 3, pp. 728-738, 2011.

[15] K. Sindhuja, M. Srinivasan, N. Niveditha, “Natural esters as an alternative to mineral oil in transformer applications”, International Journal of Pure and Applied Mathematics: IJPAM, 118(20), pp. 723–731. 2018.

[16] S. Gryglewicz, M. Stankiewicz, F. A. Oko, I. Surawska, “Esters of dicarboxylic acids as additives for lubricating oils”, Tribology International, 39(6), pp. 560-564. 2006.

[17] I. L. Hosier, C. Rogers, A. S. Vaughan, S. G. Swingler, “Ageing behavior of vegetable oil blends”, Annual Report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), pp 1-4. October 2010.

[18] M. S. Ahmad Kamal, N. Bashir and. N. A. Muhamad, "Insulating properties of vegetable oils and their blends," IEEE 7th International Power Engineering and Optimization Conference (PEOCO), Langkawi, Malaysia, pp. 455-458, 2013.

[19] S. O. Oparanti, U. M. Rao, I. Fofana, “Natural Esters for Green Transformers: Challenges and Keys for Improved Serviceability”, Energies, 16(1), 61. 2022.

[20] A. Rashid, N. Pervez, “Analysis of breakdown voltage and cost reduction of transformer oil by using nomex paper and filler”, Arabian Journal for Science and Engineering, 39(5), 3851–3857. 2014.

[21] G. D. P. Mahidhar, A. S. Karthikeyan, R. Sarathi, N. Taylor, H. Edin, “Dielectric properties of mixed mineral and synthetic ester oil”, IET Science, Measurement and Technology Technology, 14(9), 704–714.2020.

[22] J. Harwood, R. Aparicio, “Handbook of olive oil, analysis and properties”, (Springer, 2013).

[23] A. A. Suleiman., N. A. Muhamad., N. Bashir, “Effect of moisture on breakdown voltage and structure of palmbased insulation oils”, IEEE Trans. Dielectr. Electr. Insul., 21, (5), pp. 2119–2126 .2014.

[24] N. Muthulinggam, S. Partiban, “Pharmacological and non pharmacological activity of Azadirachta indica (Neem) – A review”, International Journal of Biosciences | IJB |, pp 104-112, 2014.

[25] A. Assari, T. Mahesh, E Assari, “Role of public participation in sustainability of historical city: Usage of TOPSIS method” Indian J. Sci. Technol. 5, 2289–2294. 2012.

[26] S. Chakraborty, “TOPSIS and Modified TOPSIS: A comparative analysis”, Decision Analytics Journal, Volume 2, 100021, ISSN 2772-6622. 2022.

[27] R. Karthik. and T. S. R. Raja, “Investigations of transformer oil characteristics”, IEEJ-TEE, Vol. 7, pp. 369-374, 2012.

[28] Insulating Liquids – Determination of the Breakdown Voltage at Power Frequency –Test Method, IEC 60156, Third edition, November 2003.

[29] C. P. McShane, J. Corkran, K Rapp, “Natural ester dielectric fluid development”, IEEE PES Transmission and Distribution Conf. and Exhibition, Dallas, USA, pp. 18–22. May 2006.

[30] Jeff Ong: “Biotemp, a Sensible Solution”, ABB, 2013. (Standards and Reports)

[31] Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids and Calculation of Dynamic Viscosity), ASTM D 445, 2011.

[32] B. Vahdani, S. M. Mousavi, R. Tavakkoli-Moghaddam, and H. Hashemi, “A new design of the elimination and choice translating reality method for multi-criteria group decision making in an intuitionistic fuzzy environment”, Applied Mathematical Modelling, vol. 37, no. 4, pp. 1781–1799, 2013.

[33] J. Liang and J. Pang, “Evaluation of the results of multi-attribute group decision-making with linguistic information,” Omega, vol. 40, no. 3, pp. 294–301, 2012.

[34] N. C. Chatterjee and G. K. Bose., “A COPRAS-F base multicriteria group decision making approach for site selection of wind farm,” Decision Science Letters, vol. 2, no. 1, pp. 1–10, 2013.

[35] E. Ansarifar, F. Shahidi, M. Mohebbi, S M Razavi, J. Ansarifar, "A new technique to evaluate the effect of chitosan on properties of deep-fried Kurdish cheese nuggets by TOPSIS", LWT-Food Sci. Technol. 62, 1211–1219. 2015.

[36] T. Yang. & C. Hung, "Multiple-attribute decision making methods for plant layout design problem", Robotics and Computer-Integrated Manufacturing, 23(1), 126-137. 2007.

[37] J. Rouabeh, L. M'barki, A. Hammami, I. Jallouli, A. Driss. "Studies of different types of insulating oils and their mixtures as an alternative to mineral oil for cooling power transformers", Heliyon 5 01159, 2019.

[38] Suwarno, I. S. Darma, "Dielectric properties of mixtures between mineral oil and natural ester", 2008 International Symposium on Electrical Insulating Materials (ISEIM), pp. 514-517, 2008.

[39] A. P. Cruze and K. S. Lokesh, "Ageing characteristics of alkali neutralized neem oil for liquid insulation" 2019 International Conference on High Voltage Engineering and Technology (ICHVET), Hyderabad, India, pp. 1-5. 2019.

[40] M. Martins, "Vegetable oils, an alternative to mineral oil for power transformers-experimental study of paper aging in vegetable oil versus mineral oil", Electrical Insulation Magazine, IEEE. 26. pp- 7 - 13. 2011.

[41] M Rao U. I. Fofana and J S N'cho, "On some imperative IEEE standards for usage of natural ester liquids in transformers", in IEEE Access, vol. 8, pp. 145446-145456, 2020.

[42] S. Cesa, F. Sisto, G. Zengin, D. Scaccabarozzi, A. K. Kokolakis, M. M. Scaltrito,. R Grande, M.Locatelli, F Cacciagrano, L. Angiolella, C. Campestre, A. Granese, P. Chimenti, N. Basilico, "Phytochemical analyses and pharmacological screening of Neem oil" South African Journal of Botany: Vol. 120, pp-331-337. 2019.

[43] B. A. Orhevba, O. Chukwu, Y Oguagwu, Z. D. Osunde, "Effect of moisture content on some quality parameters of mechanically expressed neem seed kernel oil". 2013.