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RESEARCH ARTICLE

Enhancement of Physical and Electrical Properties of Mustard Oil by Adding TiO_2 Nanotubes for Power Transformers

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ABSTRACT Mineral oil is the most commonly used insulating oil in power transformers due to its low cost, universal availability and high dielectric strength. The potential of vegetable oils to serve as an alternative to the conventional mineral oil for power transformers is being considered due to its better dielectric strength and high biodegradability. Furthermore, the addition of small quantity of nanotubes to vegetable oils has the potential to considerably enhance their dielectric strength. In this paper, a detailed experimental investigation on the dielectric characteristics of Mustard oil infused with Titanium dioxide (TiO_2) nanotubes has been carried out. The investigation covers the analysis of physical properties including moisture content, specific gravity, pour-point, flash point, viscosity, and acidity. Additionally, the breakdown strength and partial discharges of Mustard oil and nanofluid were also examined. All the tests were performed according to ISO and IEC standards. The detailed characterization of nanotubes was investigated with the help of X-ray diffraction and Scanning Electron Microscopy. The TiO_2 nanotubes were mixed with pure Mustard oil at the concentration levels of 0.02g/L, 0.05g/L, and 0.1g/L. The experimental results indicate that the nanofluid with a concentration of 0.05g/L exhibits better properties compared to the other samples in its potential as a replacement of the traditional mineral oil. The investigation also revealed that the AC breakdown voltage increased by approximately 40%, whereas a three-fold rise in the partial discharge extinction and inception voltages was observed when 0.05g/L TiO_2 was added into the Mustard oil compared to the pure mineral oil. A comprehensive evaluation of the dielectric properties of this mixture, in comparison to the mineral oil and other vegetable oils, underscores its cost-effectiveness as a viable alternative for power transformers. Hence, the addition of 0.05g/L TiO_2 nanofluids into Mustard oil can be considered as a practical and economically feasible substitute to both mineral and vegetable oils.

INDEX TERMS Vegetable oils, mustard oil, partial discharge analysis, mineral oil, dielectric properties, power transformers.

I. INTRODUCTION

Power transformers play a vital role in the power grids for the transmission and distribution of electrical energy. The insulation in the power transformers mainly consists of cellulose (pressboard and kraft paper) and oil. The oil acts as a liquid dielectric providing insulation to the transformer windings and serving as a coolant to manage the thermal stress and ensure heat transport [1], [2]. Mineral oil is the most commonly used insulating oil in power transformer due to its low pour point, high thermal cooling capacity, low cost, high dielectric strength, and widespread commercial availability.

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The production of mineral oil from petroleum is a non-renewable process which takes an enormous amount of time, around millions of years [3]. Furthermore, specific types, such as Askarel oils which fall under the category of polychlorinated biphenyls exhibit elevated ignition points. Nonetheless, it is important to mention that they pose severe environmental risks and are highly toxic [4], [5]. The combustion of these oils results in the production of dioxins, detrimental to aquatic life and the environment [4]. Anticipating a future shortage of mineral oil due to the non-renewable nature of petroleum-based products, a potential crisis within the transformer industry can be expected in the long run [6]. Mineral oil suffers from several drawbacks such as non-biodegradability, rendering it resistant to the decomposition by bacteria and low flammability [6], [7], [8]. Consequently, the exploration of alternative liquid dielectrics exhibiting comparable or superior properties to the mineral oil becomes imperative. In this context, vegetable oils can be considered as potential substitutes, demonstrating their improved electrical, physical, and thermal characteristics compared to the conventional mineral oil [9]. Natural esters (category of vegetable oil) have gained traction as potential replacements of conventional oils owing to their biodegradability and high flash point [9]. Vegetable oils have several advantages over the mineral oil such as high sustainability potential, lower flammability, and higher thermal stability resulting in a longer lifespan, supporting agricultural economy, renewable product, and adaptability [10]. Despite these advantages, vegetable oils exhibit higher acidity due to the presence of unsaturated fatty acids, making them chemically less stable than mineral oils. However, vegetable oils exhibit less insulation deterioration compared to the mineral oils. Hence, the utilization of vegetable oils as liquid dielectrics offers clear benefits over the mineral oils in power transformers [11], [12], [13]. Previous studies suggest that the moisture content has a less pronounced influence on the performance of natural ester fluids in combination with pressboard as opposed to its impact on mineral oil or pressboard [14]. Furthermore, vegetable oil exhibits a higher dielectric strength compared to the mineral oils when subjected to AC voltage stress [15]. However, the challenges associated with vegetable oils, such as their handling and storage complexity and price dependency on the cost of feedstock, underscore the complications involved in their utilization compared to mineral oils for power transformers.

The addition of small quantity of nanotubes into plant-based oils results in a notable enhancement of their physical and electrical properties [16]. This enhancement is attributed to the electron trapping capability of nanotubes leading to an enhancement in the dielectric strength [17]. Subsequent investigations have demonstrated a significant increase in the thermal conductivity of nanofluids in comparison to the regular vegetable oil, exhibiting the positive impact of nanoparticles incorporation [18]. For instance, addition of 0.1% of Aluminum Oxide (Al_2O_3) nanoparticles by weight in natural esters causes an increase in the dielectric strength of nanofluids [19]. However, limited research has been conducted to investigate the physical and electrical properties of Mustard oil for power transformers. In [20], AC breakdown strength of Al_2O_3 based nanofluids of Mustard oil is investigated only. Among different types of nanoparticles (metallic or non-metallic oxides), TiO_2 was found to be the best alternative to enhance the breakdown strength of insulating oils. This enhancement is attributed to the charge trap and electronegativity of nanoparticles [21]. Furthermore, when TiO_2 nanoparticles of size below 20 μm were utilized, an increase of 20% and 24% in AC and impulse breakdown voltage (BDV) was observed respectively in the base oil [22]. The TiO_2 nanoparticles are widely used with mineral and vegetable oils to enhance their thermal and absorption capability [23]. It is important to mention that there has been no research on the impact of nanotubes on the physical and dielectric properties of insulation oils for transformers in the literature.

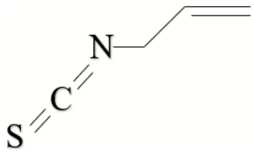

FIGURE 1. Chemical structure of mustard oil.

This paper presents the experimental study to investigate the impact of adding TiO_2 based nanotubes in Mustard oil to enhance its physical and electrical characteristics. At first, the preparation procedure of the nanofluids is presented. Next, the characterization of nanotubes is demonstrated via Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) analysis. All the samples are examined and the best sample with enhanced dielectric characteristics after comparison with mineral oil is selected. The final sample is then evaluated based on enhanced breakdown strength and partial discharge (PD) testing. Finally, the impact of sedimentation of nanotubes on Mustard oil is also investigated by examining nanofluids after regular intervals of time.

II. EXPERIMENTAL STUDIES

The chemical structure and preparation of nanofluids of Mustard oil is discussed in this section.

A. CHEMICAL STRUCTURE OF MUSTARD OIL

The chemical name of Mustard oil is allyl isothiocyanate. Mustard oil has a pale yellow oily colour. The specific gravity (density) of Mustard oil is 0.91 g/mol. It is soluble in organic solvents such as ethanol, methanol, ethers, and carbon disulphides, but not in water. Its molar mass is 99.1542 g/mol. The Molecular formula of Mustard oil is C_4H_5NS or in bonding form $CH_2 = CHCH_2N{=}C{=}S$. It is a hydrocarbon due to the bond between Carbon and Hydrogen and hence, it is a biodegradable oil. The chemical structure of Mustard can be seen in Figure 1.

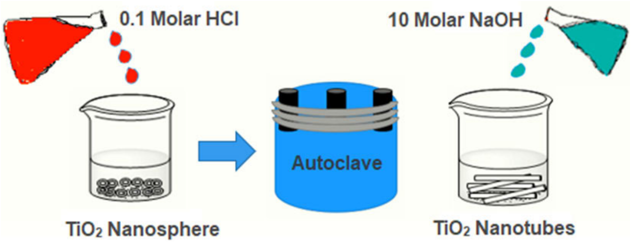

FIGURE 2. Preparation of TiO_2 nanotube.

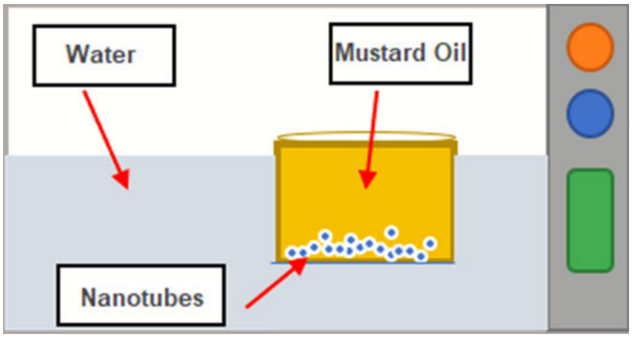

FIGURE 3. Sonication of nanotubes in mustard oil.

B. SAMPLE PREPARATION

Figure 2 illustrates the procedure of preparing TiO_2 nanotubes. Nanotubes are cylindrical structured, typically composed of carbon, metal oxides, or other materials. TiO_2 nanotubes are obtained from titanium molecules. TiO_2 nanotubes were selected because they exhibit unique characteristics of nanoscale dimensions and high surface area. Moreover, they are quite inexpensive and are more readily available than other nanoparticles [24]. Their tubular morphology allows for enhanced reactivity and efficient charge transport, making them highly desirable to increase the dielectric strength of vegetable oils. The preparation of TiO_2 nanotubes involved two steps. The first step involves the synthesis of TiO_2 nanotubes, and the second step is the preparation of nanofluids. For TiO_2 nanotubes, 1 gram of TiO nanoparticles were mixed with 10 moles solution of 50 ml sodium hydroxide and stirred constantly for 1 hour at a constant temperature of 30°C. Then, the final mixture was autoclaved at a constant temperature of 200°C for 24 hours, then cooled to the room temperature, and neutralized with 0.1 moles of HCl solution. After purification, the sample was filtered, dried at 80°C for 24 hours, and annealed for 2 hours. The nanofluid preparation involved using a water bath sonication technique to achieve a uniform dispersion of nanotubes in Mustard oil. The ultrasonicator operating at 300W was set to run for 30 minutes with an ON-OFF cycle (10 seconds ON, 5 seconds OFF) to manage thermal effects. The temperature was maintained at 25°C to avoid overheating. Precautions were taken to prevent moisture ingress, and measurements confirmed an acceptable moisture level in Mustard oil [25]. The nanofluids were prepared at three different concentrations of nanotubes:

i 0.02g/Liter TiO_2 in Mustard oil,
ii 0.05g/Liter TiO_2 in Mustard oil, and
iii 0.1g/Liter TiO_2 in Mustard oil,

TABLE 1. Quantity of TiO_2 nanotubes in mustard oil.

Amount (g/L)	0.02	0.05	0.1
Weighted Concentration (%)	0.0023	0.058	0.012

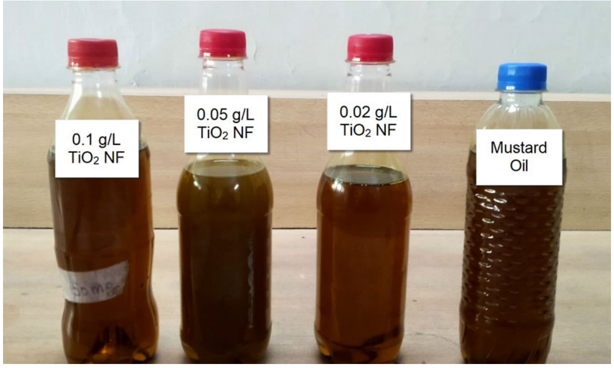

FIGURE 4. Samples in 500 ml bottles: (a) Mustard oil (b) 0.02g/L sample (c) 0.05g/L sample and (d) 0.1g/L sample.

where 0.02g/L is the lowest, 0.05 g/L is the medium, and the 0.1g/L is the higher concentrations of TiO_2 nanotubes respectively. These concentrations were chosen to assess the impact of varying nanotubes (low to high) content on nanofluid properties. The use of surfactant (oleic acid) helped to maintain stable dispersion and prevent agglomeration within the base oil.

C. PREPARED SAMPLES

The stability of TiO_2based nanofluids at each concentration was continuously monitored by observing sedimentation and agglomeration tendencies over time. This ensured that the nanofluids remained well-dispersed within acceptable parameters throughout the study duration. Prior to the addition of nanotubes to the base oil, the surface treatment process was carried out. This involved thorough cleaning to remove impurities or residues through multiple solvent washes, typically using ethanol or deionized water, followed by controlled drying. Subsequently, the nanotubes were immersed in an oleic acid solution to bond oleic acid molecules to their surface, with the surfactant concentration based on the quantity of nanotubes and expressed as a weight percentage of the nanotubes. In this study, surfactant concentrations ranged from a small amount (0.2%) to a larger amount (1%) for surface modification of nanotubes, and it is dependent on the concentration of nanotubes. The concentration of surfactant is based on the characterization of nanotubes and preparation of nanofluids. These concentrations were utilized to determine the physical and electrical properties of the nanofluids. Table 1 presents the amounts of nanotubes in g/L and corresponding weighted concentration with respect to Mustard oil.

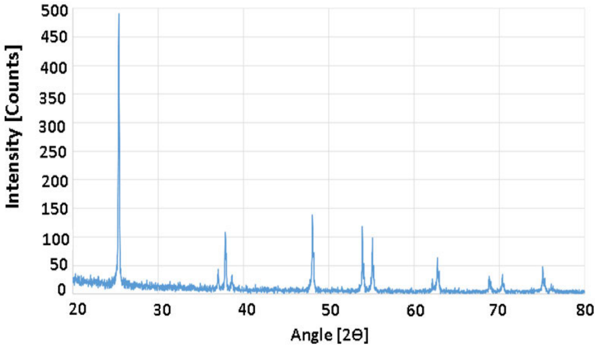

FIGURE 5. XRD Pattern of Powdered TiO_2 Nanotubes.

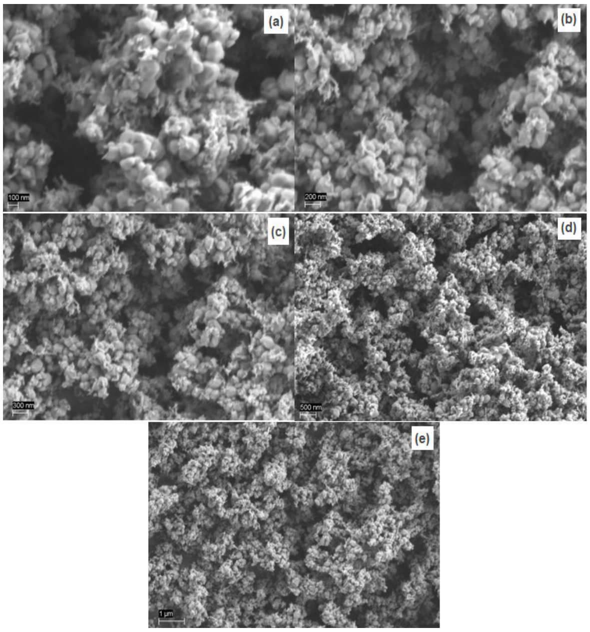

FIGURE 6. SEM Images of TiO_2 nanotubes at (a) 100-nm (b) 200-nm (c) 300-nm (d) 500-nm and (e) 1-μm.

D. CHARACTERIZATION OF NANOTUBES

XRD patterns were analyzed utilizing a Bruker AXS X-ray diffractometer employing a radiation source with a high voltage of 40 kV. The XRD analysis was conducted to determine the dimensions of TiO_2 nanotubes. Figure 5 presents the XRD pattern of powdered TiO_2 nanotubes subjected to calcination at 400°C. Figure 6 illustrates the peak values at specific 2θ angles of 25.39°, 37.86°, 48.08°, 53.93°, and 55.11° where θ represents the diffraction angle corresponding to the intensity values of (491), (108), (138), (118), and (98) counts respectively. The peak at $2\theta = 25.39°$ representing (491) exhibits the highest intensity. The prominent hexagonal pattern observed in the quartzite strongly indicates the formation of pure TiO_2 with a significant level of crystallinity. To calculate the crystal size of the powdered TiO_2, Debye Scherer equation is used as follows:

$$D = \frac{0.9\lambda}{\beta \cos\theta} \tag{1}$$

where D is the crystal size, λ is the X-ray wavelength = 0.154 nm, β is the line broadening observed from the diffraction peak whose observed value = 0.231 radians, and the diffraction angle θ corresponds to the peak intensity = 12.695°. Using the above values, the size of the crystalline TiO_2 nanotubes was calculated as 33.21 nm.

TABLE 2. Dielectric properties of TiO_2 nanotubes in mustard oil.

Dielectric Properties	Parameters	Standards
Moisture content	200 mg/kg Max.	IEC-60814
Acid number	0.6 mg KOH/g Max	IEC-62021
Viscosity	50 mm^2 Max.	ISO-3104
Pour point	-10ºC Max.	ISO-3016
Breakdown voltage	≈ 35 kV Min.	IEC-60156
Specific Gravity	Max. 1g/ml	ISO-3675
Flashpoint	200ºC Min.	ISO-2719

SEM was utilized to investigate the morphology of TiO_2 nanotubes. The experiments were conducted using a ZEISS GeminiSEM 360 operating at a voltage of 2 kV. A carbon coated grid mesh is immersed into the nanotubes for scanning. The carbon coated mesh interacts with a beam of electrons and focuses on the view of the nanotubes. Figure 6 presents SEM images of powdered TiO_2 nanotubes captured at varying scales, including 100 nm, 200 nm, 300 nm, 500 nm, and 1 μm, respectively. The SEM images clearly illustrate uniform sizing of particles as well as narrow particle size distribution.

III. PHYSICAL AND ELECTRICAL CHARACTERISTICS OF MUSTARD OIL AND NANOFLUIDS

This section presents the procedure adopted to determine the physical and electrical properties of Mustard oil.

A. PHYSICAL PROPERTIES OF MUSTARD OIL

The electrical properties of Mustard oil were analysed in accordance with IEC and ISO standards as outlined in Table 2 [26]. The parameters given in Table 2 are the minimum/maximum requirements for an insulating oil. These properties were determined using the following methods:

1. Kinematic viscosity of the vegetable oil was determined by using a viscosity bath according to IEC-3104 standard at 40°C. The time taken for a fixed volume of oil to flow through the viscometer was recorded.

2. An 877 Titrino was used to determine the acidity of the vegetable oil. About 5 grams of the oil was mixed with 20 millilitres of titrated mixture of potassium hydroxide with 2-propanoic acid according to IEC-62021 standard. The titration procedure gives the quantity of potassium hydroxide necessary for the neutralization of the acidic constituents present in the oil.

3. A coulometer was used to measure the moisture contents as per the IEC-60814 standard. Furthermore, with the help of hydrometer, the specific gravity of nanofluids was

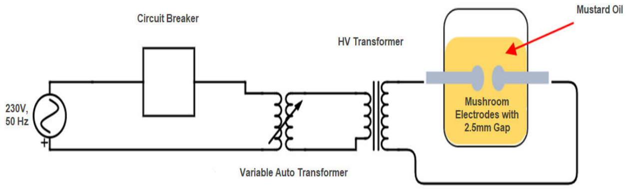

FIGURE 7. Dielectric strength setup of mustard oil and nanofluids.

determined as per ISO-4675 standard. The temperature of the oil was maintained at constant temperature of 20°C and the hydrometer was submerged into the oil. The specific gravity was calculated based on the level at which the hydrometer floated, providing a measure of the oil's density relative to the density of water.

4. The pour point of the was determined following the ISO-3016 standard by cooling the sample until its flow ceased. This test measures the lowest temperature at which the sample oil remains fluid and can help assess its performance at low-temperature environments.

5. Additionally, the flashpoint of nanofluids ware measured using an ash point tester according to ISO-2719 resulting in a maximum value of 200°C. The oil sample was gradually heated in the ash point tester until vapours were produced, and a small flame was introduced at regular intervals. The flashpoint was identified as the lowest temperature at which the oil vapour briefly ignited, providing a critical indicator of its fire safety characteristics.

B. DIELECTRIC STRENGTH OF MUSTARD OIL AND NANOFLUIDS

The dielectric strength of both, the Mustard oil and the respective nanofluids was measured according to the procedure outlined in IEC 60156 [27]. Fig. 7 presents the experimental setup for the dielectric strength testing. The experimental configuration comprises of two mushroom electrodes spaced at a distance of 2.5 mm. The voltage was incrementally raised at a rate of 2 kV per second until the insulating oil experienced breakdown. The measurements were conducted at room temperature.

C. PARTIAL DISCHARGE (PD) TESTING OF MUSTARD OIL AND NANOFLUIDS

The PD testing of Mustard oil and the variants of nanofluids was carried out according to IEC 60270 standard. The PD test setup is shown in Fig. 8 which consists of an HV testing transformer (150 kV), a limiting resistor, capacitive voltage divider and quadrupole. The PD data was transmitted to a computer via a fiber optic bus and data acquisition device. The rod-rod electrodes of diameter 6 mm each and separated by 3 mm, shown in Fig. 9, were used to generate PD signals and study PD inception voltage (PDIV) and PD extinction voltage (PDEV). The frequency bandwidth of data acquisition was set from 1 MHz to 20 MHz covering the typical PD event spectrum. The ambient noise was maintained below 30 decibels through isolation and soundproofing. A 500 ml sample was poured into a 650 ml vessel for PD testing. The voltage was incrementally raised until the apparent charge (q) reached 10 nC. The crocodile clips, calibrated for accuracy, were used to minimize the impact of impedance.

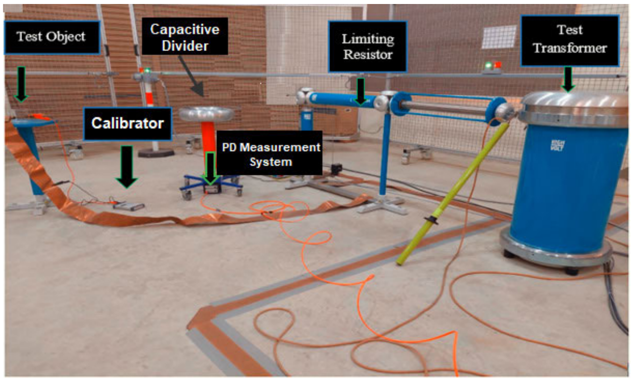

FIGURE 8. PD test setup.

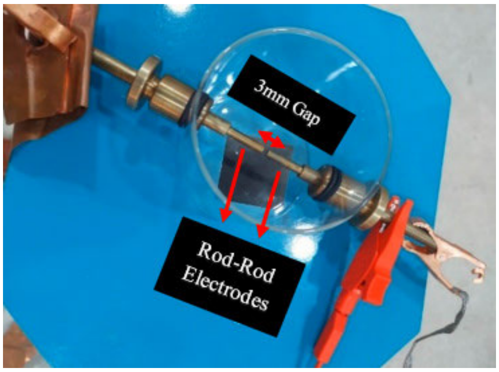

FIGURE 9. Vessel with electrodes used for pd testing.

TABLE 3. Physical characteristics of mustard oil and nanofluid samples.

Dielectric Properties	Mustard oil	0.02g/L TiO_2 sample	0.05g/L TiO_2 sample	0.1g/L TiO_2 sample
Moisture content (ppm)	60	64	65	67
Acid number (mgKOH/g)	0	0	0.008	0.01
Viscosity (mm^2/s)	40.91	43.22	43.5	44.27
Pour point (°C)	-5	-13	-32	-32
Specific Gravity (g/ml)	1	1	1	1
Flashpoint (°C)	332	345	352	355

IV. RESULTS AND DISCUSSION

This section presents the results of physical and electrical properties of nanofluids of Mustard oil.

A. PHYSICAL CHARACTERISTICS OF MUSTARD OIL AND NANOFLUIDS

The physical properties of Mustard oil and nanofluids were analysed according to the IEC and ISO standards and the

TABLE 4. BDV at different probabilities.

BDV Probability (%)	Mustard oil BDV (kV)	0.02g/L Nanofluid BDV (kV)	0.05g/L Nanofluid BDV (kV)	0.1g/L Nanofluid BDV (kV)
1.0	20	21.5	25.5	20.5
10.0	21.3	26.7	28	22
50.0	25	32	35	35.5

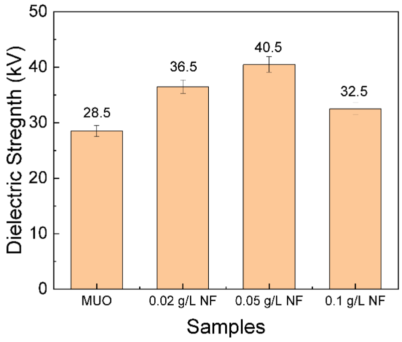

FIGURE 10. Dielectric strength of samples.

results are presented in Table 3. Following observations can be made from the presented results:

1. The increase in viscosity with higher concentration of nanotubes exhibited improved interaction among nanotubes, altering the internal structure of Mustard oil and causing it to flow more slowly.

2. Consistent acidic numbers implies that the chemical stability of the Mustard oil remains unchanged with increased concentration of nanotubes, indicating that the nanotubes do not significantly affect the acidity of the oil.

3. Minimal changes in the moisture content indicate that nanotubes have negligible impact on fluid moisture levels, implying the fluids maintain stability.

4. The stable specific gravity shows that the addition of nanotubes does not substantially affect the overall mass density of nanofluids, proving compatibility with base fluid.

5. A notable reduction in pour point with increased nanotube concentration shows the effectiveness of TiO_2 nanotubes in enhancing low-temperature fluidity, likely by preventing crystallization and improving dispersion.

6. A considerable increase in the flash point suggests an improved thermal stability of nanofluids, potentially reducing the risk of combustion when exposed to high temperatures.

B. ELECTRICAL CHARACTERISTICS OF MUSTARD OIL AND NANOFLUIDS

The dielectric strength and PD analysis of nanofluids is discussed in this subsection.

The average values of the dielectric strength of Mustard oil and nanofluid samples are presented in Fig. 10. It can be observed that the average breakdown voltage of Mustard oil and the samples is 28.5, 35.6, 40.5, and 32.5 ± 1 kV for Mustard oil, Mustard oil with 0.02 g/L nanofluid, Mustard oil with 0.05 g/L nanofluid, and Mustard oil with 0.5 g/L nanofluid

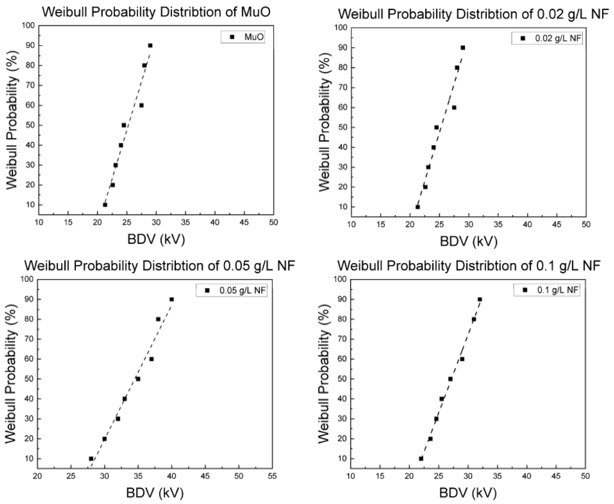

FIGURE 11. Weibull probability destruction of samples.

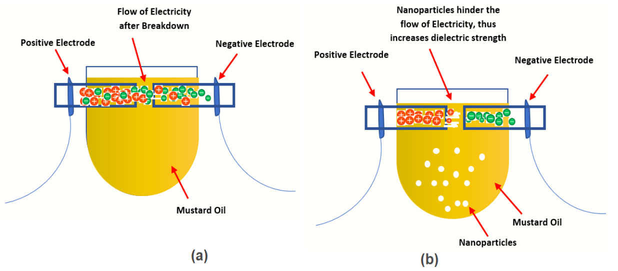

FIGURE 12. Electricity conduction in mustard oil: (a) Without nanotubes, (b) With nanotubes.

respectively. The results indicate that TiO_2 nanotubes are a good candidate to develop nanofluids for insulation oils if a suitable weighted amount is used. The Weibull probability distribution was used to determine the AC breakdown voltage of Mustard oil based TiO_2 nanofluids for different concentrations of particles, which are shown in Fig. 11. Table 4 illustrates the AC breakdown strength at breakdown probabilities of 1%, 10%, and 50% for all the nanofluids under investigation. Even at 1% or 10% probability, the values of breakdown voltage of all the nanofluids are higher than Mustard oil, which shows that the nanotubes are well dispersed and have high reliability. The AC breakdown voltage corresponding to 10 % and 50 % probabilities were evaluated. However, 10% cumulative probability represents the lowest possible breakdown voltage and gives an indication about the reliability of an insulation oil [28]. The breakdown voltage corresponding to the 1% cumulative probability is considered as the minimum possible breakdown voltage, representing the reliability of the oil. Generally, the breakdown voltage of nanofluids surpassed that of Mustard oil, regardless of the nanotube size. It was observed that the breakdown voltage of Mustard oil based TiO_2 nanofluids exhibited an increase with the increase in the concentration of nanotubes, as clear from Fig. 11. The average breakdown voltage reached its maximum value at 0.05 g/L and subsequently decreased,

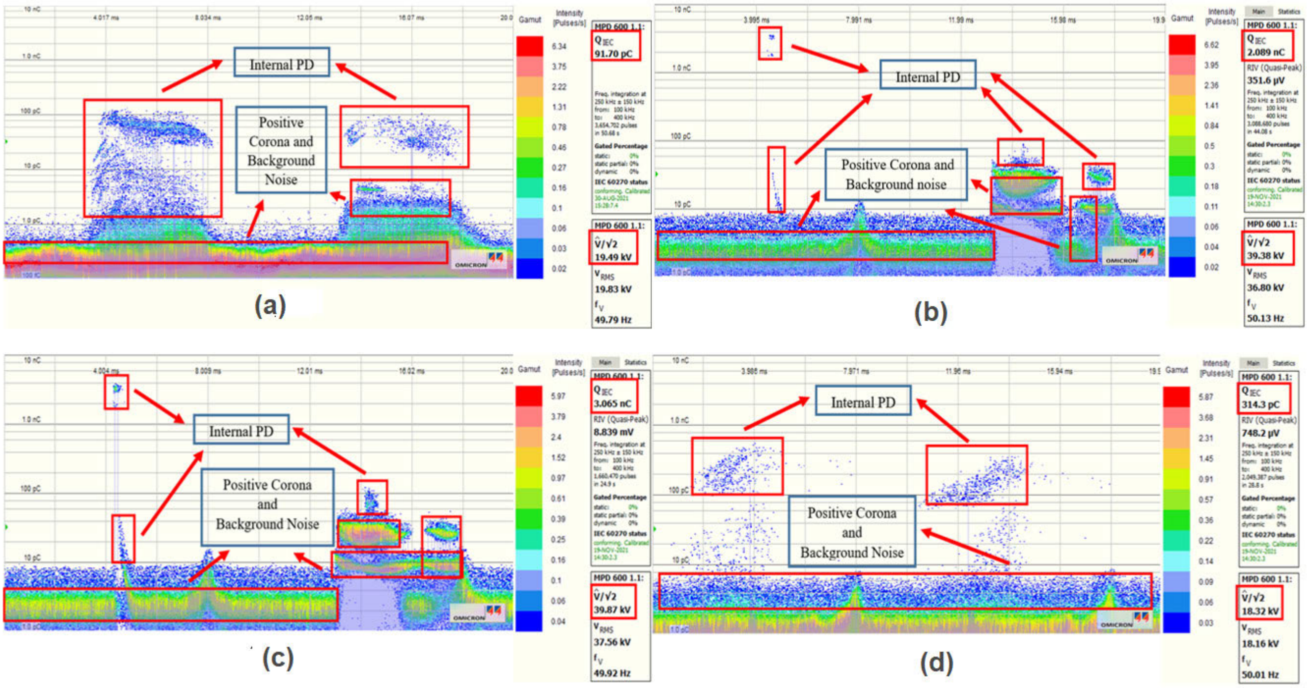

FIGURE 13. PD Pattern of (A) Mustard oil (B) 0.02g/L TiO_2 nanofluid (C) 0.05 g/L TiO_2 nanofluid (D) 0.1g/L TiO_2 nanofluid.

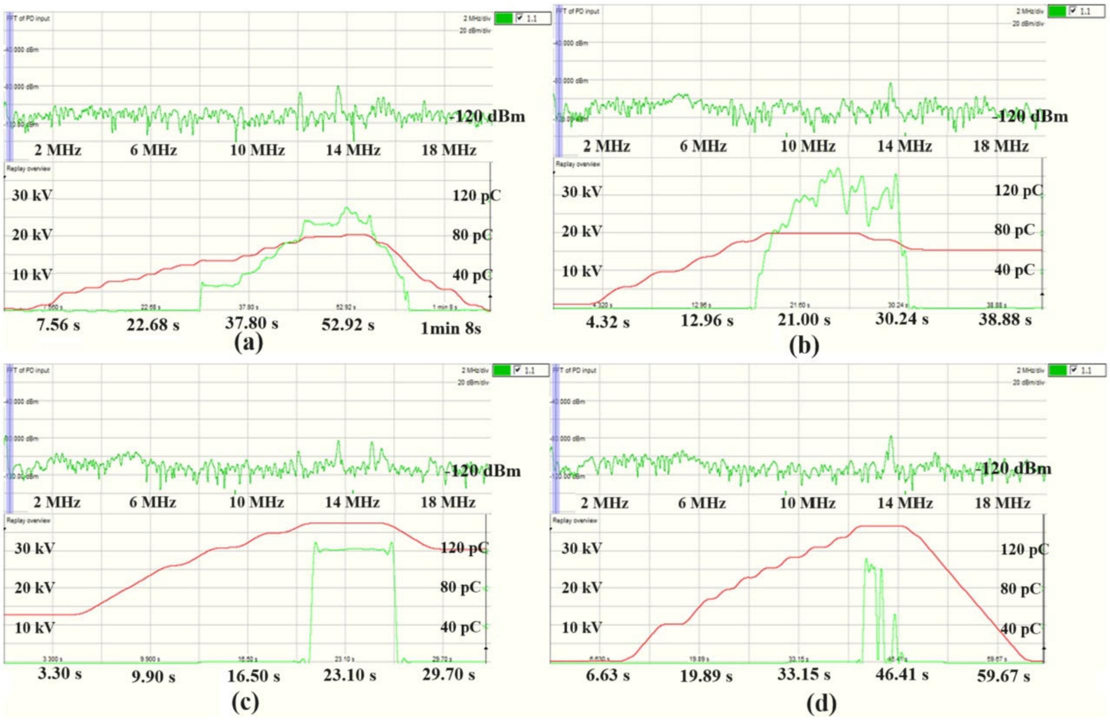

FIGURE 14. F-S V-AP plots of (A) Mustard oil (B) 0.02g/L TiO_2 sample (C) 0.05 g/L TiO_2 sample and (D) 0.1g/L TiO_2 sample.

although it remained higher than the breakdown voltage of Mustard oil.

The effect of nanotubes on dielectric fluids such as Mustard oil is further illustrated in Fig. 12 which shows that the nanotubes obstruct the charge flow between two electrodes, requiring a higher voltage to cause breakdown of the insulation. Hence, the dielectric strength of the liquids increases when nanotubes are introduced into the dielectric medium.

TABLE 5. Values for PDIV and PDEV of mustard oil and nanofluids.

Voltage	Mustard oil	0.02g/L nanofluid	0.05g/L nanofluid	0.1g/L nanofluid
PDIV (kV)	13.4	31.7	36.4	17.9
PDEV(kV)	12.3	30.2	37.1	18.2

This effect underscores the enhancement in dielectric properties attributed to the presence of nanotubes, presenting a pivotal aspect of the impact of nanotubes on the dielectric behavior of the liquid.

Table 5 presents the specific PDIV and PDEV levels for Mustard oil and the corresponding nanofluids. The results indicate a direct correlation between the concentration of nanotubes and both PDIV and PDEV. An overall increase in PDIV and PDEV is evident as the concentration of nanotubes increases, demonstrating enhanced dielectric properties of the nanofluid samples. However, a reduction in PDIV and PDEV was observed at 0.1 g/L TiO_2 sample. Interestingly, the highest PDIV and PDEV are observed at 0.5 g/L TiO_2 nanofluid sample. This reduction in PDIV and PDEV for the 0.1 g/L TiO_2 nanofluid sample is attributed to the nanotube agglomeration and clustering within the oil medium, altering the uniformity of electric field distribution. Fig. 13 presents the PD patterns for both Mustard oil and nanofluids, whereas Fig. 14 presents the voltage-amplitude curve and frequency spectrum. A considerably high PD activity is observed in the 0.5 g/L TiO_2 nanofluid sample due to its higher dielectric strength compared to the other concentration of nanofluids. Fig. 14 (a) presents an apparent charge of about 91.7pC for Mustard oil at a voltage level of 19.5kV, whereas Fig. 12 (b), (c), and (d) show apparent charge for different concentration of TiO_2. Interestingly, the 0.05 g/L TiO_2 sample exhibits the highest amount of apparent charge among all nanofluids. At lower concentration of nanotubes, the larger surface area per nanotube allows for effective charge accumulation, resulting in higher apparent charge. However, as the concentration of nanotubes increases, agglomeration reduces the available surface area per unit volume, limiting effective charge accumulation despite the overall increase in the concentration of nanotubes.

C. SEDIMENTATION AND LONG-TERM STABILITY OF NANOTUBES IN MUSTARD OIL

The homogeneous dispersion of nanotubes in an insulating fluid remains a critical concern in power transformers. Nanoparticles cluster together when they are not fully dispersed in the base oil which results in sedimentation and compromises the insulating properties of nanofluids. Therefore, a well spread mixture of nanoparticles in insulating oil is necessary for long-term stability of the insulation. In Fig. 15, a comprehensive visualization of nanotube sedimentation in Mustard oil is presented, exhibiting the settling behaviour over distinct time intervals. The sedimentation patterns are illustrated at precise time points: 0-hours, 24-hours, 48-hours, 72-hours, 96-hours, and 120-hours respectively. Notably, the sedimentation process commences at a sluggish pace and is particularly prominent after the 120-hour mark, specifically observed in the case of 0.1 g/L nanotube concentration. Achieving the optimum dispersion characteristics is crucial to improve the dielectric properties and stability of the resultant nanofluid. The detailed sedimentation analysis offers valuable insights into the dispersion stability of nanotubes in Mustard oil, affirming their well-dispersed state and optimal dispersion behaviour even at higher concentrations.

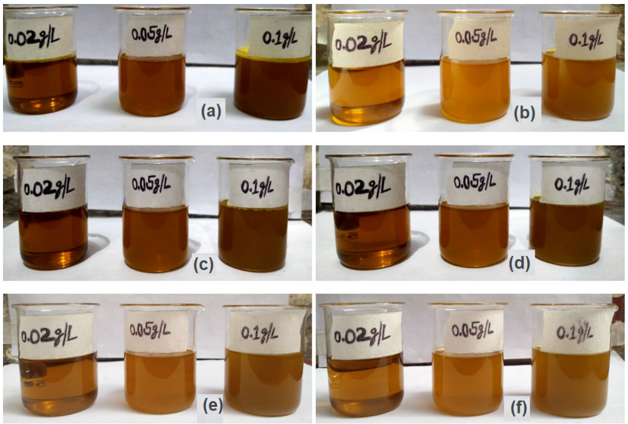

FIGURE 15. Nanotubes sedimentation observation after (a) 0-hour, (b) 24-hours, (c) 48-hours, (d) 72-hours, (e) 96-hours, and (f) 120-hours.

TABLE 6. Cost analysis of 0.05 g/L nanofluid in comparison to mineral and vegetable oils [31].

Quantities	Cost of Mineral Oil (USD)	Cost of Mustard oil (USD)	Cost of 0.05g/L-Nanofluid (USD)	Cost of Vegetable oil(s) (USD)
One Liter(s)	1.9	1.7	1.75	1.7 - 7

D. ENVIRONMENTAL IMPLICATIONS OF TiO_2 NANOFLUIDS

The environmental impacts of a nanofluids majorly depends on three main factors: (i) the type of nanoparticles being used i.e., the physical, toxic, chemical, and environmental characteristics of nanoparticles, (ii) volume or percentage of nanoparticles being used, and (iii) the method for preparation of nanoparticles [29].

The Mustard oil itself is an environmentally friendly vegetable oil. Furthermore, 0.05g/L TiO_2 is a very small quantity of nanoparticles in Mustard Oil. Although TiO_2 is a metallic oxide which has inherent toxicity and may affect living organisms, whereas 0.05 g/L is below the threshold of toxicity being inhaled by an organism to affect its internal organs [30]. Anyways, care should be taken to ensure proper sealing and immediate cleanup (in case of spoilage).

E. COST ANALYSIS

The cost-effectiveness of Mustard oil was also assessed, along with nanotubes. Table 6 provides a comprehensive

TABLE 7. Comparison of the physical and electrical characteristics of 0.05 g/L TiO nanofluid in both mineral and vegetable oil.

Dielectric Property	0.05 g/L nanofluid	Mineral oil	Vegetable oils	Ref.
Acid number (mgKOH/g)	0.008	0 - 0.12	0 - 0.04	[25]
Pour point (ºC)	-32	-39	(-25) - (-15)	[26]
AC-Dielectric Strength (kV)	40.4	20 - 36	25 - 35	[27]
Viscosity (mm^2/s)	43.5	5 - 16	15- 42	[26]
Specific gravity (g/ml)	1	0.87 – 0.92	0.83 - 0.89	[31]
Moisture Content-(wet oil)(ppm)	65	30 - 35	30 - 80	[32]
PDIV (kV)	36.4	20 - 45	25 - 45	[34]
Flash point(ºC)	352	160 -180	310 - 325	[33]
PDEV (kV)	37.1	18 - 43	14 - 43	[27]

comparative analysis demonstrating the cost-effectiveness of Mustard oil in comparison with the commonly available vegetable oils and conventional mineral oil in the market. The analysis highlights the economic viability of employing Mustard oil, especially when enhanced with nanotubes, reinforcing its potential as a cost-efficient option in comparison to conventional alternatives [31]. Table 6 highlights a noticeable cost reduction of 0.20 USD per liter of oil when comparing the suggested oil to mineral oil. Furthermore, mustard oil with 0.05g/L TiO_2 nanotubes proved to be more cost-effective than Mineral oil and other vegetable oils. Considering its cost effectiveness, it is expected that the vegetable oil will be used in power transformers after more technical evaluation of vegetable oils.

F. COMPARISON OF 0.05G/L TiO_2 SAMPLE WITH MINERAL AND VEGETABLE OILS

Table 7 provides a comprehensive comparison between 0.05g/L TiO_2 sample in terms of physical and electrical characteristics with Mineral oil and different vegetable oils [25], [26], [27], [31], [32], [33], [34]. From comparative analysis, it can be observed that the electrical characteristic of 0.05g/L TiO_2 showed significant improvement compared to the mineral and other vegetable oils. Moreover, the moisture content, flash point, and viscosity values of 0.05g/L TiO_2 based nanofluid are significantly higher compared to mineral oil, closely resembling to the values found in vegetable oils, which are within the prescribed limits as mentioned in Table 2. Although the pour point of Mustard oil exceeds that of mineral oil, it remains lower than that of typical vegetable oils. These distinctions underscore the unique properties and potential advantages of employing 0.05g/L TiO_2 over traditional mineral oil and vegetable oils.

G. POTENTIAL APPLICATIONS OF THE PROPOSED SOLUTION

Mustard oil and TiO_2 nanotubes are commonly available globally. Its various advantages, such as its biodegradability, high flash point, low toxicity, high thermal capability, cost effectiveness, and high breakdown voltage make it a suitable alternative to the conventional mineral oil. Power transformers are considered as an important component in power systems and the transformer industry makes a major contribution to the economy of a country. There is a risk of shortage of mineral oil in future which may affect the production of power transformers. Hence, an alternative oil having physical, chemical, and electrical properties equivalent with the Mineral oil is needed. The proposed TiO_2 based Mustard oil nanofluid is renewable, biodegradable, suitable dielectric parameters, and economically viable solution for such circumstances.

V. CONCLUSION

The comprehensive XRD and SEM analysis confirm the high purity and uniform distribution of TiO_2 nanotubes within the nanofluids. The observed viscosity of the nanofluids surpasses that of pure Mustard oil, aligned with the IEC standards. The negligible change in the acidic content of the nanofluids compared to Mustard oil, underscoring their chemical stability. Furthermore, specific gravity in line with IEC standards for both Mustard oil and nanofluids underscores their suitability for electrical applications. The investigation for pour and fire points exhibited promising advantages of TiO_2-based nanofluids, meeting IEC standards and demonstrating improved performance over Mineral oil. It is crucial to note that excessive nanotube loading can lead to a decline in dielectric strength, emphasizing the need for an optimized concentration. This establishes 0.05g/L TiO_2 is cost effective alternative to the mineral and other vegetable oils. The optimum quantity of nanotubes to be used in the base oil can only be determined after conducting such experiments with different quantities (low to high) of nanoparticles.

This study primarily focuses on TiO_2 nanotubes; however, future research should explore a broader spectrum of nanotubes and their combinations to unveil even more tailored and optimized dielectric properties. Additionally, quantifying the precise impact of moisture on the dielectric strength and exploring methods to mitigate its effects would contribute significantly to practical applications. To the best of author's knowledge, this is the first attempt to investigate the impact of nanotubes on the insulation oils and gives a pathway towards the utilization of nanotubes for evaluating the dielectric properties of insulation oils. Moreover, different nanotubes (metallic and nonmetallic oxides) can be used and tested to obtain a better insight of the impact of different nanotubes on vegetable oils.

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