

## Impact Of $\text{TiO}_2$ Nanoparticle on AC Breakdown Voltage of Rice Bran Oil in The Presence of Cetyl Trimethyl Ammonium Bromide (CTAB)

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### ABSTRACT

*In electrical insulation systems, the selection of dielectric fluids is critical to ensuring the reliable and efficient operation of power transformers. Traditionally, mineral oil—also known as transformer oil—has been widely used due to its effective insulating and cooling properties. However, due to growing environmental concerns, researchers are increasingly exploring alternative oils. Natural ester oils, such as rice bran oil, have emerged as promising candidates for replacing mineral oil. This study investigates the potential of rice bran oil enhanced with titanium oxide ( $\text{TiO}_2$ ) nanoparticles as a biodegradable insulating fluid. Nanotechnology is employed to improve the dielectric performance, with a focus on AC breakdown voltage. Additionally, Cetyl-Trimethyl Ammonium Bromide (CTAB) is used as a stabilizing agent to prevent nanoparticle agglomeration and enhance dispersion stability in the fluid. The effects of varying  $\text{TiO}_2$  concentrations (0.005 wt%, 0.01 wt%, and 0.05 wt%) and the presence of CTAB (0.01 g) are evaluated in both rice bran oil and mineral oil. Experimental results indicate that the optimal concentration—rice bran oil with 0.01 wt%  $\text{TiO}_2$  and 0.01 g CTAB—achieves a maximum AC breakdown voltage of 74.03 kV. This suggests that rice bran oil-based nanofluids offer a viable and environmentally sustainable alternative to conventional mineral oil in transformer insulation applications.*

*Keywords: Insulation oil; AC breakdown voltage; alternative oil; rice bran oil; nanoparticle*

### INTRODUCTION

Generally, a transformer is a device that consists of coils that transmit electrical energy from one AC circuit to one or multiple other circuits, with the ability to step up or down the voltage. A malfunction in a transformer result in economic losses due to an interruption in power supply increases the replacement cost and time-consuming to repair. It is crucial to ensure the transformer's safety when it is in use. Transformer post-failure research shows that a transformer's life mostly depends on the state of the insulation system. There are two types of transformers which are oil-filled and dry-type. Generally, oil-filled transformers are commonly used to transmit electrical energy over long distances. The oil functions as both an

insulator and a coolant, allowing transformers to operate efficiently and increasing their power transfer capability (LV et al. 2017; Suhaimi et al. n.d.; Rajňák et al. 2020). Extended use of transformers can lead to failures, particularly within the insulation system, resulting in electrical breakdown of the liquid insulation. Transformer oil, also known as insulating oil, is used in oil-filled transformers to provide both electrical insulation and cooling to the windings and core (Wang et al. 2019). It is often likened to the “blood” of the transformer due to its essential role in maintaining reliable operation (Shen et al. 2021). It must be periodically tested to monitor the condition of the transformer. To operate safely and effectively, transformer oil is necessary to protect the winding of the transformer from contaminants and

moisture, which can lead to corrosion and insulation failure. There are two common types of transformer oil used in the industry: paraffin-based transformer oil and naphtha-based transformer oil. Both types of oils are formulated to minimize failures and electrical breakdowns. While each has its own advantages, sludge formed in naphtha-based oil tends to be more soluble than that in paraffin-based oil, making it less likely to settle at the bottom of the transformer (Mohd Tukiman et al. 2021). This makes the oil circulation in the transformer make the cooling system operate well. The standard for power transformers is IEEE Std C57.12.00-1993 which is general requirements for liquid-immersed distribution, power, and regulation transformers. The standard will control insulation of oil and be updated over time.

Mineral oil (MO) has been widely used in power transformers for over 150 years. Derived from petroleum, MO offers several beneficial electrical and thermal properties that make it suitable for transformer applications. Key advantages include its low cost, broad availability, and low viscosity (Masra et al. 2022). It is commonly used in oil-filled transformers across a wide voltage range—from distribution to transmission levels. However, MO is gradually falling out of favor due to its poor biodegradability. In the event of leakage, it can contaminate soil and water, raising serious environmental concerns (Charalampakos et al. 2019; Hamid et al. 2022; Olmo et al. 2020; Ye et al. 2020; Zhong et al. 2013). As the demand for alternative oil sustainable and environmentally friendly increases, researchers and industry are exploring vegetable-based dielectric fluids to replace conventional mineral oil in transformers. Rice bran oil, obtained from renewable sources, has emerged as a quality-enhancing substitute for transformer applications. As the demand for sustainable and high-performance dielectric fluids increases, the exploration of alternative insulating oils becomes essential. This study proposes rice bran oil (RBO) as a potential replacement for mineral oil (Hamid et al. 2022).

Rice bran oil is a vegetable oil extracted from the outer layer of the brown rice kernel, which makes up 6-8% of the paddy rice. In 2014, more than 50 million tonnes of rice bran oil were produced from 741 million tonnes of paddy. Though it hasn't been utilized in transformers yet, rice bran oil is commonly used for fuel, cooking, and biodiesel. There have only been a few studies done with RBO, particularly on its electrical, chemical, and physical characteristics. It is a potential alternative to mineral oil for use as transformer oil due to its highly flammable non-biodegradability and low flash point (Hamid et al. 2022). According to the researchers, there are 4 most significant differences between mineral oil and rice bran oil as shown in Table 1.

TABLE 1. The Physicochemical properties of RBO and MO

Parameter	RBO	MO
Appearance	Light yellow	Bright
Flash Point (oc)	297	135
Pour Point (oc)	-33	-40
Viscosity (mm <sup>2</sup> /s)	42	8

As an additional alternative, this research incorporates titanium dioxide (TiO<sub>2</sub>) nanoparticles to enhance the dielectric characteristics of rice bran oil (RBO). The use of TiO<sub>2</sub> as a dielectric fluid modifier has been investigated as a method to improve dielectric strength (Khandai, Mishra, & Roy, n.d.). To ensure nanoparticle dispersion and stability, the surfactant cetyl trimethyl ammonium bromide (CTAB) is employed as a stabilizing agent. This study aims to evaluate the effect of TiO<sub>2</sub> nanoparticles on the AC breakdown voltage of RBO in the presence of CTAB and to determine the withstand voltage using statistical analysis.

According to Barhoum et al. (2022), a nanomaterial is any material natural, accidental, or manufactured that contains particles in an unbounded state and has one or more exterior dimensions for at least 50% of the particles in the number size distribution. Nanoparticles, nanofibers, nanotubes, nanowires, nanorods, nanosheets, and droplets are a few types of nanomaterials. Nanoparticles are extremely small particles with dimensions typically ranging from 1 to 100 nanometres, where one nanometre is equivalent to one billionth of a meter. Over the years, researchers have explored nanoparticles since the term “nanotechnology” was first used by Norio Taniguchi in 1974. There are 3 types of nanoparticles found by researchers which are conductive nanoparticles: aluminium oxide (Al<sub>2</sub>O<sub>3</sub>), semiconductive nanoparticles: titanium dioxide (TiO<sub>2</sub>) or cadmium sulphite (Cds), and nonconductive magnetic nanoparticles: iron (III) oxide (Fe<sub>2</sub>O<sub>3</sub>) or ferric oxide (Suhaimi et al. 2020). Among the various types examined, titanium oxide (TiO<sub>2</sub>) nanoparticles have been found to enhance breakdown strength. This improvement is attributed either to the function of TiO<sub>2</sub> nanoparticles as charge traps (Du et al. 2012) or to their electronegativity. When TiO<sub>2</sub> nanoparticles with an average particle size of less than 20 nm were used, the AC and impulse breakdown voltages increased by approximately 120% and 124%, respectively, compared to the base oil (Atiya et al. 2015).

A surfactant, short for surface-active agent, is a chemical compound that lowers the surface or interfacial tension between two liquids, a liquid and a gas, or a liquid and a solid. It contains molecules with both hydrophilic (water-attracting) and hydrophobic (water-repelling) regions, which makes it effective in a variety of applications.

This dual nature allows them to interact with both water and oil thus enabling water to mix, form foam, and facilitate the detachment of dirt (Atiya et al. 2015). In this context, the relationship between surfactants and nanomaterials often comes into play in the field of nanotechnology when dealing with the dispersion and stabilization of nanoparticles. Surfactants are used to disperse and stabilize the nanoparticles within the oil to prevent the nanoparticles from aggregating. This is essential to ensure a uniform distribution throughout the oil and create a stable colloidal system where the nanoparticles are effectively dispersed thus can prevent undesirable interactions that could impact the performance of the oil.

According to the study, surfactant concentrations were categorized into three ranges: low (0.1% and 0.3%), medium (0.6% and 1%), and high (1.5%). Optical Microscope Analysis showed that increasing concentration beyond these levels led to significant agglomeration in the samples, as illustrated in Figure 1. This is likely due to the formation of a double chain around the nanoparticle surfaces. Therefore, lower concentrations of surfactants are recommended as the optimal choice. Furthermore, as shown in the TEM image for a low surfactant concentration in Figure 2, most of the  $\text{TiO}_2$  nanoparticles were well-separated and distinguishable from one another. The shadow in the image is attributed to residual oil droplets on the coated grid. The maximum agglomeration observed was approximately 200 nm, located in the upper part of the image. Surfactants play a crucial role in reducing nanoparticle agglomeration. However, excessive surfactant amounts can adversely affect dispersion. These results indicate that using a low concentration of surfactants makes the dispersion of nanoparticles more stable than that without surfactants or with an excess amount of surfactant (Atiya et al. 2015).

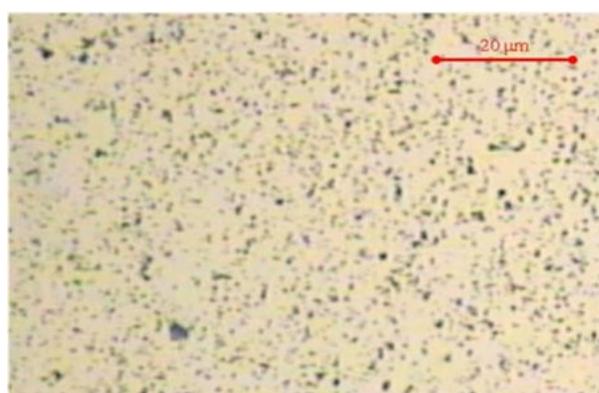


FIGURE 1. Small concentration of surfactant using optical Microscope Analysis

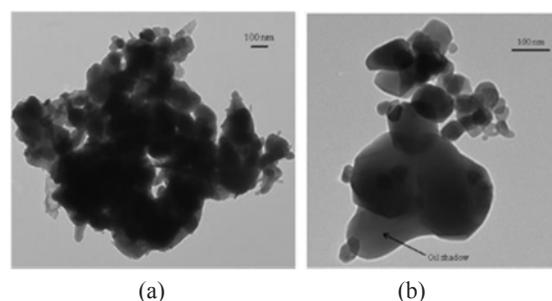


FIGURE 2. TEM image of oil-based nanofluids (a) with surfactant and (b) without surfactant

## METHODOLOGY

### NANOFLUID PREPARATION

The two-step method is a common approach for preparing nanofluids, which are fluids containing nanoparticles dispersed in a base fluid which is RBO. The first step involves creating or obtaining nanoparticles, like metal oxides or carbon-based particles. The nanoparticles that are used for this study are Titanium Dioxide ( $\text{TiO}_2$ ). In this study, commercial nanoparticles are purchased to ensure a consistent and well-characterized product. The second step is where these nanoparticles are dispersed evenly into a base fluid, using techniques such as ultrasonication or magnetic stirring to prevent clumping. Surfactants are added to aid dispersion to ensure that the nanofluid maintains stability over time. Figure 3 shows a general process for nanofluid preparation.

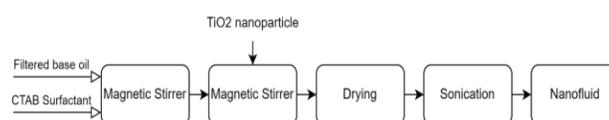


FIGURE 3. Process for nanofluid preparation

Before the process of nanofluid starts, the base oil must filter through a membrane filter with a pore size of  $0.2\mu\text{m}$  to obtain a clean oil sample free of impurities and unwanted particles. To enhance dispersion behavior, a surfactant was employed along with nanoparticles. A specific amount of CTAB was added to the base oil. The mixture was then stirred under magnetic conditions for 30 minutes at 90 degrees Celsius and 520 rpm using the Magnetic Stirrer MR Hei-Tec. CTAB plays a crucial role

in stabilizing the nanoparticles in the oil. 500 mL of base oil (RBO) was used for each nanoparticle concentration. The nanofluids for testing were prepared with concentrations of  $\text{TiO}_2$  0.005 wt%, 0.01 wt%, and 0.05 wt%. The mixture underwent magnetic stirring for an additional 30 minutes. Subsequently, the sample was dried to eliminate moisture content and allowed to cool gradually. The nanofluid underwent vacuum drying at 85 °C for 2 days to further decrease moisture content. Then, it cooled to room temperature for more than 30 minutes. Additionally, the sonication process was crucial to de-agglomerate the particles. Nanoparticles aggregate due to strong van der Waals forces, impacting nanofluid stability. This process took an average of 30 minutes using Qsonica Sonicators (Mohd Tukiman et al. 2021).

### AC BREAKDOWN VOLTAGE TEST

The AC breakdown voltage test is a standardized method used to evaluate the dielectric strength of insulating materials under alternating current conditions. In this test, a sample of the nanofluid is placed in a test cell with electrodes immersed in the sample. The voltage at the breakdown is recorded as the AC breakdown voltage, providing crucial information about the material's ability to withstand electrical stress.

The AC breakdown test was conducted using the BAUR DTA 100C, which has a maximum output voltage of 100 kV as shown in Figure 4. The horizontal VDE configuration (mushroom to mushroom) installed in the AC breakdown test equipment represents a quasi-uniform electric field (Figure 5). The AC breakdown voltage was tested with a 2.5 mm gap distance in a cubic glass container with a volume of 400 ml, following the IEC 60156 standard. The voltage was increased at a rate of 2 kV/s, with an initial standing time of 5 minutes before applying the voltage. The time interval between each measurement was set to 2 minutes. A total of 18 breakdown readings were taken for each oil sample. The tests were performed at atmospheric pressure and room temperature (23–26°C). The AC breakdown tester applied AC voltage at a frequency of 50 Hz across the test cell filled with the oil samples. The average breakdown voltages and standard deviations were calculated based on the 18 measurements for each oil sample.



FIGURE 4. Automatic BAUR DTA 100C oil tester



FIGURE 5. VDE configuration

### STATISTICAL ANALYSIS

The Weibull distribution is a widely used statistical method for analyzing the probability distribution of breakdown voltages in electrical and mechanical systems. This reliability technique is employed to model the material strength and time to failure of various components. The breakdown voltage data is used to fit the Weibull distribution curve, from which the 1% breakdown probability and 50% breakdown probability (mean) can be determined. The withstand voltage is a statistically distributed quantity that corresponds to a failure probability, depending on the electrical stress applied to the liquid insulation. The Weibull distribution approach is generally accepted as the best fit for data approximating failure and dielectric strength in the field of electrical insulation. The cumulative function of the Weibull distribution is given in Equation (1), where 'α' is the scale parameter and 'β' is the shape parameter.

$$F(x) = 1 - e^{-\frac{x^\beta}{\alpha}}, x \geq 0 \quad (1)$$

## RESULTS AND DISCUSSION

In this study, there were two different types of RBO nanofluid used to study the AC breakdown voltage of oil samples. The first sample was without a presence surfactant, CTAB. The second sample was with the presence of a surfactant, CTAB. The concentration of CTAB used for every sample was 0.1%. The difference of AC breakdown voltage test of RBO nanofluid with the presence of surfactant were shown in Figure 6 and detail values have been tabulated in Table 2.

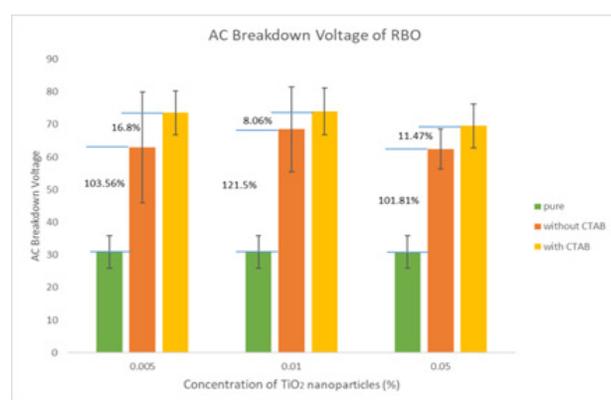


FIGURE 6. AC breakdown voltage of RBO nanofluid

The percentage difference of breakdown voltage between RBO nanofluid can be calculated based on (Suhaimi et al. n.d.) using Eq (2), where  $V_2$  is higher voltage and  $V_1$  is lower voltage.

$$V\% = \left( \frac{V_2 - V_1}{V_1} \right) \times 100 \quad (2)$$

Figure 6 shows that the AC breakdown voltage increases with the addition of TiO<sub>2</sub> nanoparticles. In addition, the presence of CTAB further increases the AC breakdown voltage compared to the cases without CTAB and the pure RBO. For example, at 0.005% TiO<sub>2</sub> concentration, the AC breakdown voltage of pure RBO was 30.93 kV. Adding TiO<sub>2</sub> without CTAB increased the voltage by 103.56%, while the addition of CTAB resulted in a further 16.8% improvement. For 0.01% TiO<sub>2</sub>, the voltage increase without CTAB was 121.5%, with CTAB providing an additional 8.06% increase. At 0.05% TiO<sub>2</sub>, the respective increases were 101.81% and 11.47%.

The introduction of TiO<sub>2</sub> nanoparticles into Rice Bran Oil (RBO) enhances its AC breakdown voltage, a crucial parameter for the effectiveness and reliability of electrical insulation systems. This enhancement is likely due to the improved dielectric properties and increased electron

scattering, which suppresses the initiation and propagation of electrical discharge (LV et al. 2018). The schematic diagram in Figure 7 represents how the free electrons trap in the transformer oil with nanoparticles.

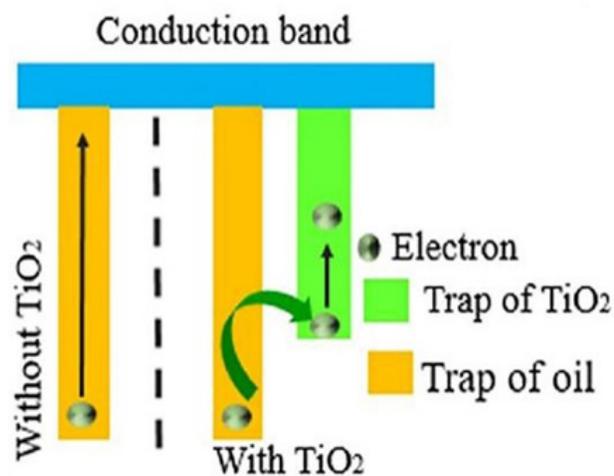


FIGURE 7. Charge transfer in nanofluids

According to the researcher (Bhunja et al. 2021), when there is no nanomaterial dispersed in the oil, the field-ionization induced electrons in the oil will participate in the breakdown process. It became conduction electrons and propagated towards the opposite electrode instantly. These electrons drift towards the opposite electrode to cause breakdown. With nanomaterials like TiO<sub>2</sub> dispersed in the oil, which have different permittivity and conductivity compared to the oil, the field-ionization induced electrons will be attracted toward the nanomaterials. Depending on the conductivity and permittivity of the nanomaterials, the electrons will reside on the nanomaterial surfaces for a certain time. This is called trapping of the electrons by the dispersed nanomaterials. The electrons from the field-ionization of the oil get attracted toward the TiO<sub>2</sub> nanomaterials and get captured in shallow traps of the TiO<sub>2</sub>. The TiO<sub>2</sub> holds those electrons for a longer time compared to the oil. This delays the shortening of the electrodes and hence increases the breakdown strength of the oil.

However, the effectiveness of these nanoparticles is greatly influenced by their dispersion stability within the oil. Without proper dispersion, nanoparticles tend to agglomerate, forming larger clusters that are less effective at enhancing dielectric properties and can even create weak points that lower the breakdown voltage. To overcome this, the addition of a surfactant such as CTAB (Cetyltrimethylammonium Bromide) plays a critical role. CTAB improves the dispersion of TiO<sub>2</sub> nanoparticle by reducing the surface tension between the nanoparticles and the oil, preventing agglomeration (Atiya et al. 2015). This leads to a more uniform distribution of nanoparticles

throughout the oil, which enhances the stability and dielectric performance of the nanofluid. The results in the graph demonstrate that with CTAB, the AC breakdown voltage of RBO increases even further compared to the same concentrations  $\text{TiO}_2$  without the surfactant. This improvement is consistent across various concentrations of  $\text{TiO}_2$ , indicating that CTAB effectively facilitates the optimal dispersion of nanoparticles, thereby maximizing their dielectric contribution. Other than that, as shown in the graph, the error bars indicate some variability in the measurements. The error bars vary in length across different samples. For instance, the samples without CTAB

generally show longer error bars compared to those with CTAB and pure RBO, indicating higher variability in the measurements. This higher variability could be due to the dynamic interactions between CTAB and the  $\text{TiO}_2$  nanoparticles, which might lead to inconsistencies in nanoparticle dispersion and therefore in the breakdown voltage measurements (Atiya et al. 2015). Based on the research (Atiya et al. 2015), in nanofluids without surfactant, the dielectric properties are mainly due to the nanoparticles, with minimal influence from the interfacial zone.  $\text{TiO}_2$  nanofluids exhibit higher breakdown strength due to the nanoparticles' ability to attract and trap electrons.

TABLE 2. Identification of selected muscle and electrode placement position

Presence of Surfactant CTAB	Concentration of $\text{TiO}_2$ (%)	Average (kV)	Standard Deviation (kV)	Minimum (kV)	Maximum (kV)
	0 (Pure)	30.93	4.95	23.1	38.1
0g	0.005	62.96	16.95	27.4	81.2
	0.01	68.51	12.90	37.9	88.1
	0.05	62.42	6.06	49.9	70.3
	0.005	73.54	6.77	63	87.5
0.01g	0.01	74.03	7.19	57.5	84.3
	0.05	69.58	6.74	46.1	78.2

The dielectric constant increases with more nanoparticles due to their higher dielectric constant compared to oil, but the confinement of oil chains at the interfacial zone slightly lowers the dielectric constant in  $\text{TiO}_2$  nanofluids compared to both the oil and the nanoparticles. Figure 8 shows the structure of interfacial zone oil based nanofluids.

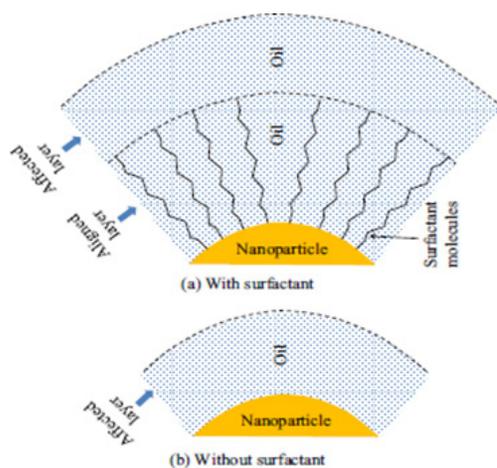


FIGURE 8. Structure of interfacial zone oil based nanofluids

As shown in Figure 8(a), the addition of a surfactant alters the interfacial structure around the nanoparticles. The surfactant promotes better dispersion and reduces the formation of rigid molecular layers, resulting in higher polarization and, consequently, an increased dielectric constant. In contrast, Figure 8(b) illustrates the case without a surfactant, where the interfacial zone consists of two distinct layers. The first is the aligned layer, characterized by a rigid structure that is difficult to polarize. Surrounding this is the affected layer, which contains less aligned oil chains but is still influenced by the rigidity of the inner layer. This dual-layer structure limits overall polarization, leading to a lower dielectric constant compared to the surfactant-enhanced system. The rigid structure also allows electrons to lose energy more easily, increasing the breakdown strength. The increase in AC breakdown voltage is noticeable even at low concentrations of  $\text{TiO}_2$  (0.005%). However, the percentage increase is most significant at 0.01% concentration. Beyond this, at 0.05%, the relative improvement due to the addition of CTAB decreases slightly, indicating a possible saturation effect or optimal concentration for dielectric enhancement.

## STATISTICAL ANALYSIS OF AC BREAKDOWN VOLTAGE

To evaluate the oil's, withstand voltage, a 1% probability of failure must be estimated. The estimated values from the Weibull distribution (1% and 50% probability) are given in Table 3. 1% Probability of Failure represents a very low probability of failure, indicating the voltage level at which only 1% of samples are expected to fail. This is crucial for ensuring the high reliability and safety of the electrical insulation system. Meanwhile, a 50% Probability of Failure represents a median failure rate, meaning that 50% of the samples are expected to fail at this voltage. This is commonly used as a standard measure for industry and utilities (Hamid et al. 2022).

TABLE 3. Weibull distribution of 1% probability AC withstands voltage.

Presence of Surfactant CTAB	Concentration of TiO <sub>2</sub> (%)	1% AC Withstand Voltage (kV)
NO	0 (pure)	18.69
	0.005	33.24
	0.01	48.53
	0.05	42.54
	0.005	52.49
YES	0.01	59.04
	0.05	58.99

Introducing TiO<sub>2</sub> to RBO significantly enhances the 1% AC withstand voltage. The withstand voltage increases with the concentration of TiO<sub>2</sub> up to 0.01%, showing the highest voltage of 48.53 kV. A slight decrease is observed at 0.05% TiO<sub>2</sub> (42.54 kV), indicating that beyond a certain concentration, the benefit might decrease because of some factors, for example agglomeration of nanoparticles. Adding CTAB substantially improves the withstand breakdown voltage across all TiO<sub>2</sub> concentrations. For 0.005% TiO<sub>2</sub>, the voltage increases from 33.24 kV to 52.49 kV with CTAB, a significant improvement. For 0.01% TiO<sub>2</sub>, the voltage improves from 48.53 kV to 59.04 kV with CTAB. For 0.05% TiO<sub>2</sub>, the voltage increases to 58.99 kV with CTAB.

Similar results were obtained when adding surfactant will improve the breakdown voltage. CTAB enhances the dispersion of TiO<sub>2</sub> particles, leading to better performance even at lower concentrations. During the design of a transformer, the withstand voltage of the transformer's liquid is always used to meet the safety requirements of the insulation systems. Even though a withstand value ensures that the transformer liquids will not fail as a dielectric, it can be considered as a level where the risk of failure is acceptably low (Wang & Wang, 2012).

## COMPARATIVE ANALYSIS

This research stands out for utilizing rice bran oil, a sustainable and nutrient-rich byproduct often overlooked in mainstream studies. This choice not only contributes to waste reduction but also promotes the exploration of underutilized natural resources. Table 4 presents a comparison between this research and other studies.

Atiya (Atiya et al. 2015) conducted an experiment using rice bran oil and TiO<sub>2</sub> nanoparticles at the same concentration (0.01%) but with a smaller particle size (<50 nm), achieving an AC breakdown voltage of 53.2 kV. In our research, we achieved a higher AC breakdown voltage of 74.03 kV, exceeding the results presented in (Atiya et al. 2015). This emphasizes that factors beyond nanoparticle size, such as the inclusion of CTAB, play a crucial role in enhancing electrical performance, making the material combination in this study much more effective. In other research (Khandai, Mishra, & Roy, 2015), which used mineral oil and TiO<sub>2</sub> nanoparticles at the same 0.01% concentration recorded an AC breakdown voltage of 30kV which is lower than our method. This highlights the performance and sustainability advantages of rice bran oil over mineral oil. This further underscores that the innovative use of CTAB and eco-friendly alternatives in this study not only significantly outperforms the mineral oil research but also provides a greener and more efficient solution for electrical insulation.

Table 4. Comparative analysis

	Oil	TiO <sub>2</sub> (%)	CTAB (g)	Size (nm)	AC Breakdown Voltage (kV)
This study	RBO	0.01	0.01	>100	74.03
Atiya (2015)	RBO	0.01	-	>50	53.20
Khandai S (2015)	MO	0.01	-	-	30

## CONCLUSION

The study reveals significant enhancements in the AC breakdown voltage of Rice Bran Oil (RBO) when TiO<sub>2</sub> nanoparticles are added. Even at low concentrations, the nanoparticles substantially improve the dielectric properties of the oil by creating barriers to electron movement and suppressing the initiation of electrical discharges. This improvement is consistent across various concentrations of TiO<sub>2</sub>, demonstrating the potential of nanoparticle incorporation in enhancing the insulating capabilities of RBO.

Moreover, the presence of the surfactant CTAB (Cetyltrimethylammonium Bromide) can improve the breakdown voltage of the RBO nanofluid. CTAB enhances the dispersion stability of TiO<sub>2</sub> nanoparticles, preventing agglomeration and ensuring a more uniform distribution within the oil, thereby maximizing the dielectric enhancement provided by the nanoparticles. This leads to a noticeable increase in breakdown voltage compared to RBO with nanoparticles but without CTAB, highlighting the surfactant's role in optimizing the performance of the nanofluid. Using the Weibull distribution to model the breakdown voltage data provides a method for estimating withstand voltages at different probabilities of failure, crucial for assessing the reliability and safety of the insulating material.

Overall, adding TiO<sub>2</sub> nanoparticles and CTAB to RBO significantly improves its insulation properties, making it a good choice for use in high-voltage electrical systems like transformers. This makes these oils more reliable and efficient, which is important for the safety and performance of electrical equipment

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#### DECLARATION OF COMPETING INTEREST

None.

#### REFERENCES

- Atiya, E. G., Mansour, D. E. A., Khattab, R. M., & Azmy, A. M. 2015. Dispersion behavior and breakdown strength of transformer oil filled with TiO<sub>2</sub> nanoparticles. *IEEE Transactions on Dielectrics and Electrical Insulation* 22(5): 2463–2472.
- Barhoum, A., et al. 2022. Review on natural, incidental, bio-inspired, and engineered nanomaterials: History, definitions, classifications, synthesis, properties, market, toxicities, risks, and regulations. *Nanomaterials* 12(2).
- Bhunia, M. M., Panigrahi, K., Naskar, C. B., Bhattacharjee, S., Chattopadhyay, K. K., & Chattopadhyay, P. 2021. 2D square nanosheets of anatase TiO<sub>2</sub>: A surfactant-free nanofiller for transformer oil nanofluids. *Journal of Molecular Liquids* 325.
- Charalampakos, V. P., Peppas, G. D., Pyrgioti, E. C., Bakandritsos, A., Polykrati, A. D., & Gonos, I. F. 2019. Dielectric insulation characteristics of natural ester fluid modified by colloidal iron oxide ions and silica nanoparticles. *Energies* 12(17).
- Du, Y., et al. 2012. Effect of semiconductive nanoparticles on insulating performances of transformer oil. *IEEE Transactions on Dielectrics and Electrical Insulation* 19(3): 770–776.
- Hamid, M. H. A., et al. 2022. Electrical properties of palm oil and rice bran oil under AC stress for transformer application. *Alexandria Engineering Journal* 61(11): 9095–9105.
- Jasper, D., Khandai, S., Mishra, A. P., & Roy, N. K. 2020. Investigation on electrical characteristics of ester oil with TiO<sub>2</sub> nanoparticles. In *2020 IEEE-HYDCON* (pp. 1–4). IEEE.
- LV, Y., Rafiq, M., Li, C., & Shan, B. 2017. Study of dielectric breakdown performance of transformer oil based magnetic nanofluids. *Energies*, 10(7).
- LV, Y., et al. 2018. Effect of nanoparticle morphology on pre-breakdown and breakdown properties of insulating oil-based nanofluids. *Nanomaterials* 8(7).
- Masra, S. M. W., Arief, Y. Z., Sahari, S. K., Muhammad, M. S., Rigit, A. R. H., & Rahman, M. R. 2022. A systematic review on promising development of palm oil and its nanofluid as a biodegradable oil insulation alternative. *IEEE Transactions on Dielectrics and Electrical Insulation* 29(1): 302–318.
- Mohd Tukiman, M. H., Suhaimi, N. S., Md Din, M. F., Abdul Rahman, A. R., & Mohd Ishak, M. T. (2021). Electrical properties of waste mineral oil recycled under various treatments and doping with nanoparticles for transformer application. In *2021 IEEE International Conference in Power Engineering Application (ICPEA)* (pp. 198–203). IEEE.
- Olmo, C., Méndez, C., Ortiz, F., Delgado, F., & Ortiz, A. 2020. Titania nanofluids based on natural ester: Cooling and insulation properties assessment. *Nanomaterials* 10(4).
- Rajňák, M., et al. 2020. Statistical analysis of AC dielectric breakdown in transformer oil-based magnetic nanofluids. *Journal of Molecular Liquids* 309.
- Shen, Z., Wang, F., Wang, Z., & Li, J. 2021. A critical review of plant-based insulating fluids for transformers: 30-year development. *Renewable and Sustainable Energy Reviews*.
- Suhaimi, N. S., Md. Din, M. F., Ishak, M. T., & Abdul Rahman, A. R. 2018. Statistical analysis on AC breakdown voltage of CNT nanofluid with mineral oil and palm oil. In *2018 IEEE 7th International Conference on Power and Energy (PECon)* (pp. 111–116). IEEE.

- Suhaimi, S. N., Abdul Rahman, A. R., Md Din, M. F., Hassan, M. Z., Ishak, M. T., & Bin Jusoh, M. T. 2020. A review on oil-based nanofluid as next-generation insulation for transformer application. *Journal of Nanomaterials* 2020.
- Wang, X., & Wang, Z. D. 2012. Study of dielectric behavior of ester transformer liquids under AC voltage. *IEEE Transactions on Dielectrics and Electrical Insulation* 19(6): 1916–1925.
- Wang, Z., Zhou, Y., Lu, W., Peng, N., & Chen, W. 2019. The impact of TiO<sub>2</sub> nanoparticle concentration levels on impulse breakdown performance of mineral oil-based nanofluids. *Nanomaterials* 9(4).
- Ye, W., Hao, J., Zhu, M., Li, J., & Liao, R. 2020. Low temperature breakdown behavior analysis of natural esters from the perspective of molecular structure. *Journal of Molecular Liquids* 318.
- Zhong, Y., et al. 2013. Insulating properties and charge characteristics of natural ester fluid modified by TiO<sub>2</sub> semiconductive nanoparticles. *IEEE Transactions on Dielectrics and Electrical Insulation* 20(1): 135–140.