Impact of Fe$_3$O$_4$, CuO and Al$_2$O$_3$ on the AC Breakdown Voltage of Palm Oil and Coconut Oil in the Presence of CTAB

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Abstract: This paper presents an experimental study on the AC breakdown voltages of Refined, Bleached and Deodorized Palm Oil (RBDPO) Olein and Coconut Oil (CO) in the presence of conductive (Iron (II,III) Oxide, Fe$_3$O$_4$), semi-conductive (Copper (II) Oxide, CuO) and insulative (Aluminium Oxide, Al$_2$O$_3$) nanoparticles without and with surfactant. The type of surfactant used in this study was Cetyl Trimethyl Ammonium Bromide (CTAB). The volume concentrations range of Fe$_3$O$_4$, CuO and Al$_2$O$_3$ was varied from 0.001% to 0.05%. Transmission Electron Microscope (TEM) was used to characterize the nanoparticles in RBDPO and CO. AC breakdown voltage tests were carried out for RBDPO and CO of which the AC breakdown voltage at 1% probability was determined based on Weibull distribution. It is found that only Al$_2$O$_3$ can improve the average AC breakdown voltage of RBDPO and CO. The AC breakdown voltages at 1% probability for RBDPO and CO can be improved through introduction of Fe$_3$O$_4$, CuO and Al$_2$O$_3$ at certain volume concentrations. Al$_2$O$_3$ provides the highest enhancement of AC breakdown voltages at 1% probability for RBDPO and CO with the highest percentage of improvement can be up to 52%. CTAB has no clear effect on the improvement of AC breakdown voltages of RBDPO and CO based Fe$_3$O$_4$, CuO and Al$_2$O$_3$ nanofluids.

Keywords: AC breakdown voltage; refined bleached and deodorized palm oil; coconut oil; Fe$_3$O$_4$; CuO; Al$_2$O$_3$; nanofluids

1. Introduction

It is known that nanoparticles are able to enhance the cooling properties, thermal conductivity/diffusivity and electrical characteristics of insulation fluids [1–4]. Previous works have examined thoroughly the electrical parameters of nanofluids which include the initiation voltage, discharge propagation and streamers [5,6]. The effects of nanoparticles on insulation fluids are known to be dependent upon the intrinsic properties, volume concentrations, solid-liquid contact areas, suspension by surfactants and synthesis methods [7,8].

The synthesis method of dispersing nanoparticles in insulation fluids can be carried out either by one- or two-step methods. In one-step method, the dispersion of nanoparticles is carried out directly
into the base fluids. However, this method is not recommended for large quantities of nanofluids due to the incomplete reaction and stabilization [9,10]. In two-step method, nanoparticles are dispersed into the base fluids by automated mixers such as magnetic stirrer, high-shear mixers and bead mills. Sonication is used to ensure uniform dispersion of nanofluids and surfactant decrease agglomeration and prevent sedimentation of nanofluids. In addition, the electrostatic and steric stabilities of insulation fluids against agglomeration can be improved with introduction of surfactants. Surfactants could adsorb at the interface between nanoparticle and insulating fluid and change the dielectric and thermal characteristics of nanofluids [8,11].

Previous works have examined the mineral oil and vegetable oil based nanofluids based on electrically conductive, semi-conductive and insulative nanoparticles which focus on the AC/lightning breakdown voltage, streamer, partial discharge, dielectric properties and thermal ageing [3–6,10–21]. Majority of the studies focus on the AC breakdown voltages examination whereby different types of nanoparticles such as Iron (II,III) Oxide (Fe₃O₄), Iron (III) Oxide (Fe₂O₃), Zinc Oxide (ZnO), Silicon Oxide (SiO₂), Titanium Oxide (TiO₂), Aluminium Oxide (Al₂O₃), Copper (II) Oxide (CuO), Zirconium Dioxide (ZrO₂), Multi-wall Carbon Nanotubes (MWCNT) and Aluminium Nitride (AlN) have been considered [4,5,11,19–38]. Both mineral- and vegetable-based nanofluids have been tested for AC breakdown voltage and the performance improvements up to 256% and 63% have been recorded [35,37]. In addition, different types of surfactants such as Cetyl Trimethyl Ammonium Bromide (CTAB), oleic acid, Sodium Dodecyl Sulfonate (SDS), silane coupling agent Z6011, Sodium Dodecyl Benzene Sulfonate (SDBS) and Octadecylamine Acetate (ODA) have been examined of which several noticeable impacts are observed [5,11,22,25–27,30,33,36,38]. Overall, the AC breakdown voltage studies of nanofluids conclude that the positive effects will normally take place at low level of volume percentage concentrations of nanoparticles [11,22,27,30]. In addition, the types of surfactants used for the nanofluids can also affect the AC breakdown voltage performances [27,38].

Most of the AC breakdown voltage studies on vegetable-based nanofluids focused on crops such as rapeseed, palm, soybean, corn and coconut [5,20,22,24–26,29,33,35]. A study in Reference [5] reveals that the average AC breakdown voltage of rapeseed oil increases by 20% with the introduction of Fe₃O₄ and oleic acid [5]. Other study shows that the introduction of Fe₃O₄ could reduce the AC breakdown voltage at 1% probability for Palm Fatty Acid Ester (PFAE) by 5%. However, both TiO₂ and Al₂O₃ could increase the AC breakdown voltage at 1% probability for PFAE by 14% and 7% respectively [20]. In the presence of ZnO and TiO₂, the AC breakdown voltages of soybean ester oil can increases by 41% and 63% while palm ester oil can increase by 44% and 54% respectively [25]. Other studies in References [24,29] show that the introduction of TiO₂ and SiO₂ in natural ester FR3, increase the AC breakdown voltage by 31% and 33%. Currently, the studies on the effect of nanoparticles on Refined, Bleached and Deodorized Palm Oil (RBDPO) Olein and Coconut Oil (CO) are still limited. In addition, further knowledge is needed to confirm the impact of Fe₃O₄, CuO and Al₂O₃ on the AC breakdown voltage performances on vegetable oils. This paper presents the initiative to further understand the impact of three types of nanoparticles on the AC breakdown voltage performances of RBDPO and CO. Conductive (Fe₃O₄), semi-conductive (CuO) and insulative (Al₂O₃) nanoparticles are used in this study. The impact of CTAB is also examined and all samples are tested for AC breakdown voltages. Weibull distribution is used for the analysis on the AC breakdown voltage at 1% probability.

2. Materials and Methods

2.1. Materials

Two types of RBDPO Olein were examined as samples for palm oil. Meanwhile, virgin CO was used for the other type of vegetable oil. The fats content and vitamin E and A of the RBDPO and CO are shown in Table 1. The distribution of the fatty acids for all RBDPO and CO were determined by Gas Chromatography (GC) based on MPOB test methods, p.3.4:2004 and p.3.5:2004 [39]. The contents
of saturated fats and unsaturated fats among the RBDPO are almost similar and it is lower than CO which is dominated by saturated fats, as shown in Table 1.

| Types of Fats | Types of Fatty Acids | RBDPOA GC (%) | MD (g) | RBDPOB GC (%) | MD (g) | CO GC (%) | MD (g) |
|---------------|----------------------|----------------|--------|----------------|--------|-----------|--------|
| Saturated     | C6: Caproic          | -              | -      | -              | -      | -         | -      |
|               | C8: Caprylic         | -              | -      | -              | -      | -         | -      |
|               | C10: Capric          | -              | -      | -              | -      | -         | -      |
|               | C12: Lauric          | 0.3            | 45.4   | 0.3            | 43.0   | 48.6      | 92.8   |
|               | C14: Myristic        | 1.1            | 0.9    | 20.0           |        |           |        |
|               | C16: Palmitic        | 37.7           | 39.3   | 9.5            |        |           |        |
|               | C18: Stearic         | 3.9            | 4.2    | 3.2            |        |           |        |
| Monounsaturated | C18: Oleic          | 42.3           | 43.0   | 43.0           | 43.0   | 6.0       | 3.6    |
| Polyunsaturated | C18: Linoleic       | 12.4           | 11.6   | 10.4           |        | 1.1       | 3.6    |
|               | C18: Linolenic       | 0.3            | 11.6   | 0.2            | 14.0   | -         | -      |
| Vitamin E     | -                    | 4.4 × 10⁻³     | -      | 75 × 10⁻³      | -      | -         | -      |
| Vitamin A     | -                    | 264 × 10⁻⁶     | -      | -              | -      | -         | -      |

* GC = Gas Chromatography; MD = Manufacturer’s Datasheet; RBDPOA = Refined, Bleached and Deodorized Palm Oil A; RBDPOB = Refined, Bleached and Deodorized Palm Oil B; CO = Coconut Oil.

The types of nanoparticles used in this study were conductive nanoparticle, Fe₃O₄, semi-conductive nanoparticle, CuO and insulative nanoparticle, Al₂O₃. The basic properties of Fe₃O₄, CuO and Al₂O₃ nanoparticles are shown in Table 2. The Al₂O₃ size is lower than both Fe₃O₄ and CuO. The colour of Fe₃O₄ and CuO are black while Al₂O₃ is white. The densities of Fe₃O₄, CuO and Al₂O₃ are 5.17 g/cm³, 6.31 g/cm³ and 3.96 g/cm³ respectively.

| Properties | Fe₃O₄ | CuO | Al₂O₃ |
|------------|-------|-----|-------|
| Size (nm)  | 50–100 | <50 | 40    |
| Appearance colour | Black | Black | White |
| Density (g/cm³) | 5.17 | 6.31 | 3.96 |
| Relative permittivity | 80 | 18.1 | 9.9 |
| Electrical conductivity (S/m) | 1 × 10⁴–1 × 10⁵ | 1 × 10⁷ | 1 × 10⁻¹² |
| Thermal conductivity (W/m.K) | 4–8 | 76.5 | 30 |

To attain suspension stability against sedimentation of nanoparticles, CTAB was used in this study. The shape of CTAB is solid spherical and white in colour as shown in Table 3.

| Properties | CTAB |
|------------|-----|
| Description | Cationic |
| Form | Solid |
| Colour | White |
| Melting point (°C) | 248–251 |
| Flash point (°C) | 244 |
| Flammability | Not flammable |

2.2. Preparation of Nanofluids

Three times filtration of all RBDPO and CO were carried by a membrane filter with a pore size of 0.2 µm before the synthesis process. The first part of synthesis procedure of RBDPO and CO based Fe₃O₄, CuO and Al₂O₃ nanofluids was carried out without CTAB as shown in Figure 1. The Fe₃O₄, CuO and Al₂O₃ were first dispersed individually into either RBDPO and CO through a Fisher Scientific
isotemp heated magnetic stirrer at 800 rpm. After 30 min of stirring, the oil samples were rested at ambient temperature for 30 min. Next, the oil samples were dried through an air circulating oven at 85 °C for 48 h.

For the second part of synthesis with CTAB, RBDPO and CO were suspended individually with CTAB for 30 min by a magnetic stirrer as shown in Figure 2. The concentration of CTAB under study is 50% of the volume concentration of nanoparticles. It is based on the similar study in Reference [33] where the optimum concentration of surfactants is found at that concentration level. Next, the Fe$_3$O$_4$, CuO and Al$_2$O$_3$ were added individually into oil samples of which the stirring time was maintain for 30 min. Ultrasonic Homogenizer—Model 300VT was used to ensure well dispersion of Fe$_3$O$_4$, CuO, Al$_2$O$_3$ and CTAB in the oil samples and to reduce the agglomeration time. The sonication was carried out for 1 h. In total, 30 min of resting time at ambient temperature was given to the oil samples before it was subjected to drying process in an air circulating oven for 48 h at 85 °C. The final procedure was to rest the oil samples for 24 h at ambient temperature before the AC breakdown voltage measurement. The oil samples were stirred by magnetic stirrer during the AC breakdown voltage test as per ASTM D1816 [41]. The volume percentage concentrations of Fe$_3$O$_4$, CuO and Al$_2$O$_3$ used in this study were 0.001%, 0.025%, 0.035% and 0.05%. The moisture for the nanofluids could not be determined after the drying procedure for both synthesis processes due to difficulties to assess the commercial moisture measurement tester. However, based on the same drying procedure for base oil, the moisture ranges for RBDPOA, RBDPOB and CO are 143 ppm, 134 ppm and 150 ppm based on measurements by Metrohm 831 Karl Fischer (KF) Coulometer as per ASTM D6304 [42].
2.3. Nanoparticle Characterization

The morphology of the RBDPO and CO based Fe$_3$O$_4$, CuO and Al$_2$O$_3$ nanofluids were observed by JEOL JEM-2100F high-resolution transmission electron microscope (HRTEM). The point and lattice resolutions of the equipment can be up to 0.23 nm and 0.1 nm. The oil samples were first diluted with distilled water and one drop of diluted sample was placed on the copper grid. Next, the copper grid was placed for 15 min on a drop of uranyl acetate solution for staining purpose before placed in filter paper. Overnight drying of the copper grid was carried out at room temperature before viewed by HRTEM. For this measurement, only RBDPO and CO based Fe$_3$O$_4$, CuO and Al$_2$O$_3$ nanofluids with volume percentage concentrations of 0.05% were analyzed.

2.4. AC Breakdown Voltage

The AC breakdown voltage test was carried out based on ASTM D1816 at ambient temperature ranging between 25 °C and 34 °C. The AC breakdown voltage was carried by BAUR DPA 75C of which the oil samples were poured into a 500 mL test cell [41]. The equipment can measure AC breakdown voltage up to 75 kV ± 1 kV. VDE electrodes, each with a diameter of 36 mm were used for the test. The gap distance between electrodes was set to 1 mm. A uniform rise rate of 0.5 kV/s was subjected to the oil samples until the breakdown. The oil samples were stirred continuously during the breakdown. For each of the oil samples, 5 min resting interval time was given to ensure the breakdown by-products and bubbles dispersed out from the electrodes. In total, the average of 50 breakdown measurements was recorded for analysis.

3. Results

3.1. Effect of Fe$_3$O$_4$ Nanoparticle on RBDPO and CO

Transmission Electron Microscope (TEM) images of the RBDPOA, RBDPOB and CO after 0.05 % addition of Fe$_3$O$_4$ without and with CTAB can be seen in Figure 3. The agglomerations of Fe$_3$O$_4$ for oil samples without CTAB shown in Figure 3a–c are more apparent as compared to oil samples with CTAB shown in Figure 3d,e.

![Image of TEM images](image-url)

**Figure 3.** Transmission Electron Microscope (TEM) images for (a) Refined, Bleached and Deodorized Palm Oil A (RBDPOA), (b) Refined, Bleached and Deodorized Palm Oil B (RBDPOB) and (c) Coconut Oil (CO) without the presence of CTAB and (d) RBDPOA, (e) RBDPOB and (f) CO with the presence of CTAB at 0.05% of Fe$_3$O$_4$.

Generally, the introduction of Fe$_3$O$_4$ generally causes reduction of AC breakdown voltage for RBDPO and CO without and with CTAB. Without CTAB, the AC breakdown voltage reduction trend for RBDPOA is almost linear as the volume concentrations of Fe$_3$O$_4$ increases from 0.001% to 0.05% as shown in Figure 4a. The AC breakdown voltage of RBDPOA decreases by 33% after addition 0.05%
of Fe$_3$O$_4$. The same pattern is observed for RBDPOB except that there is a minor increment of AC breakdown voltage after 0.05% addition of Fe$_3$O$_4$. The AC breakdown voltage trend for CO is different from RBDPO where 0.001% of Fe$_3$O$_4$ initially causes significant reduction of AC breakdown voltage. With 0.025% addition of Fe$_3$O$_4$, the AC breakdown voltage of CO increases almost exponentially as the volume concentration of Fe$_3$O$_4$ increase to 0.05%.

![Figure 4](image-url)

**Figure 4.** Effect of Fe$_3$O$_4$ on the AC breakdown voltage of RBDPO and CO (a) without CTAB and (b) with CTAB.

The reductions of AC breakdown voltages are higher for oil samples with CTAB than without CTAB as shown in Figure 4b. Significant reductions of AC breakdown voltages are found for the oil samples after 0.025% addition of Fe$_3$O$_4$. The highest percentages of AC breakdown voltage reductions for RBDPOA, RBDPOB and CO are 46%, 48%, 37% after 0.05%, 0.035%, 0.05% addition of Fe$_3$O$_4$ respectively.

The AC breakdown voltages of different concentration of Fe$_3$O$_4$ at 1% probability are tabulated in Table 4 which have been determined by cumulative Weibull distribution function with scale parameter ($\alpha$), shape parameter ($\beta$) and measured data ($t$) shown in Equation (1).

$$F(t|\alpha,\beta) = 1 - e^{-\left(\frac{t}{\alpha}\right)^\beta}$$

(1)

**Table 4.** AC breakdown voltage of Refined, Bleached and Deodorized Palm Oil (RBDPO) and Coconut Oil (CO) at 1% probability at different concentration of Fe$_3$O$_4$.

| Samples  | Volume of Concentration (%) | Breakdown Voltage at 1% Probability (kV) | Without CTAB | With CTAB |
|----------|-----------------------------|-----------------------------------------|--------------|-----------|
|          |                             |                                         |              |           |
| RBDPOA   | 0                           | 21.60                                   | 21.60        | 21.60     |
|          | 0.001                       | 27.69                                   | 25.27        |           |
|          | 0.025                       | 20.72                                   | 14.90        |           |
|          | 0.035                       | 14.82                                   | 17.88        |           |
|          | 0.05                        | 15.86                                   | 10.40        |           |
| RBDPOB   | 0                           | 25.88                                   | 25.88        | 25.88     |
|          | 0.001                       | 27.17                                   | 33.93        |           |
|          | 0.025                       | 24.58                                   | 13.81        |           |
|          | 0.035                       | 19.68                                   | 15.29        |           |
|          | 0.05                        | 24.32                                   | 25.88        |           |
| CO       | 0                           | 27.21                                   | 27.21        |           |
|          | 0.001                       | 11.64                                   | 27.32        |           |
|          | 0.025                       | 18.96                                   | 19.54        |           |
|          | 0.035                       | 24.31                                   | 26.44        |           |
|          | 0.05                        | 30.03                                   | 17.29        |           |
It is shown that 0.001% addition of Fe\textsubscript{3}O\textsubscript{4} can increase the AC breakdown voltages at 1% probability for most of the oil samples without and with CTAB as shown in Table 4. Only CO without CTAB shows enhancement of AC breakdown voltages at 1% probability at volume concentration of 0.05%. The highest percentage of improvement for AC breakdown voltage at 1% probability can be up to 31% for RBDPOB with CTAB. There is no clear improvement effect of CTAB on the of AC breakdown voltage at 1% probability for Fe\textsubscript{3}O\textsubscript{4}.

3.2. Effect of CuO Nanoparticle on RBDPO and CO

The TEM images for CuO disperse in RBDPO and CO without and with CTAB at volume concentration of 0.05% can be seen in Figure 5. For both RBDPO, the agglomerations of CuO decrease as CTAB is added as shown in Figure 5a,b,d,e. On the other hand, the TEM images in Figure 5c,f show no clear effect of CTAB on the agglomerations of CuO in CO.

![TEM images](image_url)

**Figure 5.** TEM images for (a) RBDPOA, (b) RBDPOB and (c) CO without the presence of CTAB and (d) RBDPOA, (e) RBDPOB and (f) CO with the presence of CTAB at 0.05% of CuO.

A similar pattern is observed as Fe\textsubscript{3}O\textsubscript{4} for CuO whereby majority of the AC breakdown voltages for RBDPO and CO decrease as the volume concentration of CuO increases. Without CTAB, the AC breakdown voltage of RBDPOA initially decreases as the volume concentration of CuO increases to 0.025% as shown in Figure 6a. As the volume concentration of CuO increases to 0.05%, the AC breakdown voltage of RBDPOA slightly increases but at a much lower level than the base oil. RBDPOB experiences significant reduction of AC breakdown voltage with 0.001% addition of CuO. As the volume concentration of CuO increases from 0.025% to 0.05%, the AC breakdown voltage of RBDPOB increases almost linearly to a final value of 34.1 kV. The AC breakdown voltage of CO decreases almost exponentially as the volume concentration of CuO increases.

The introduction of CTAB leads to further reduction of AC breakdown voltages for the oil samples as shown in Figure 6b. The oil samples show a steady decrement trend of AC breakdown voltages as the volume concentrations of CuO increases. The final AC breakdown voltages of RBDPOA, RBDPOB and CO after 0.05% addition of CuO are 16.3 kV, 16.8 kV and 16.1 kV respectively.

The introduction of CuO can only improve AC breakdown voltages at 1% probability for RBDPOA as seen Table 5. The highest percentages of AC breakdown voltage improvements for without and with CTAB are 16% and 27% after 0.035% and 0.001% addition of CuO. After introduction of CuO, RBDPOB and CO experience significant reductions of AC breakdown voltages at 1% probability either without or with CTAB.
A similar pattern is observed as Fe$_3$O$_4$ for CuO whereby majority of the AC breakdown voltages for RBDPO and CO decrease as the volume concentration of CuO increases. Without CTAB, the AC breakdown voltage of RBDPOA initially decreases as the volume concentration of CuO increases to 0.025% as shown in Figure 6a. As the volume concentration of CuO increases to 0.05%, the AC breakdown voltage of RBDPOA slightly increases but at a much lower level than the base oil. RBDPOB experiences significant reduction of AC breakdown voltage with 0.001% addition of CuO. As the volume concentration of CuO increases from 0.025% to 0.05%, the AC breakdown voltage of RBDPOB increases almost linearly to a final value of 34.1 kV. The AC breakdown voltage of CO decreases almost exponentially as the volume concentration of CuO increases.

The introduction of CTAB leads to further reduction of AC breakdown voltages for the oil samples as shown in Figure 6b. The oil samples show a steady decrement trend of AC breakdown voltages as the volume concentrations of CuO increases. The final AC breakdown voltages of RBDPOA, RBDPOB and CO after 0.05% addition of CuO are 16.3 kV, 16.8 kV and 16.1 kV respectively.

![Figure 6. Effect of CuO on AC breakdown voltage of RBDPO and CO (a) without CTAB and (b) with CTAB.](image)

Table 5. AC breakdown voltage of RBDPO and CO at 1% probability at different concentration of CuO.

| Samples | Volume of Concentration (%) | Breakdown Voltage at 1% Probability (kV) |
|---------|-----------------------------|----------------------------------------|
|         |                             | Without CTAB | With CTAB               |
| RBDPOA  | 0                           | 21.60        | 21.60                   |
|         | 0.001                       | 19.36        | 27.44                   |
|         | 0.025                       | 17.84        | 26.13                   |
|         | 0.035                       | 25.01        | 24.23                   |
|         | 0.05                        | 18.42        | 6.36                    |
| RBDPOB  | 0                           | 25.88        | 25.88                   |
|         | 0.001                       | 20.02        | 21.56                   |
|         | 0.025                       | 16.76        | 22.22                   |
|         | 0.035                       | 24.39        | 21.50                   |
|         | 0.05                        | 22.60        | 7.98                    |
| CO      | 0                           | 27.21        | 27.21                   |
|         | 0.001                       | 22.35        | 21.21                   |
|         | 0.025                       | 21.02        | 15.41                   |
|         | 0.035                       | 19.65        | 15.01                   |
|         | 0.05                        | 22.67        | 9.33                    |

3.3. Effect of Al$_2$O$_3$ Nanoparticle on RBDPO and CO

The effect of CTAB on the agglomerations of Al$_2$O$_3$ in the oil samples is not as clear as Fe$_3$O$_4$ and CuO as shown in Figure 7. For RBDPOA, it seems that the introduction of CTAB increases the agglomerations of Al$_2$O$_3$ as seen in Figure 7d. The agglomeration for RBDPOB seems almost unchanged with introduction of CTAB as shown in Figure 7e. On the other hand, CTAB reduces the agglomerations of Al$_2$O$_3$ for CO as seen in Figure 7f.

Without CTAB, there are increment patterns of AC breakdown voltages for RBDPOA and CO as the volume concentration of Al$_2$O$_3$ increases as seen in Figure 8a. The AC breakdown voltage of RBDPOA increases by 12% with 0.035% addition of Al$_2$O$_3$. Meanwhile, 0.05% addition of Al$_2$O$_3$ increases the AC breakdown voltage of CO by 12%. For RBDPOB, the AC breakdown voltage fluctuates at 40.6 kV and 42.1 kV as the volume concentration of Al$_2$O$_3$ increases. Only a minor increment of AC breakdown voltage for RBDPOB is found.

The patterns of AC breakdown voltages are slightly different for oil samples with CTAB as compare to without CTAB as seen in Figure 8b. The AC breakdown voltage of RBDPOA still shows AC breakdown voltage increment pattern as the volume concentration of Al$_2$O$_3$ increases. The highest percentage of AC breakdown voltage increment for RBDPOA is 18% after 0.035% addition of Al$_2$O$_3$. 

![Figure 8. Effect of Al$_2$O$_3$ Nanoparticle on AC breakdown voltage of RBDPO (a) without CTAB and (b) with CTAB.](image)
For RBDPOB, the AC breakdown voltage slightly decreases as 0.001% of Al$_2$O$_3$ is added and maintains as the volume concentration of Al$_2$O$_3$ increases. The AC breakdown voltage of CO decreases steadily as the volume concentration of Al$_2$O$_3$ increases until 0.035%. The AC breakdown voltage increases by 7% with 0.05% addition of Al$_2$O$_3$.  

![Figure 7](image1)

**Figure 7.** TEM images for (a) RBDPOA, (b) RBDPOB and (c) CO without the presence of CTAB and (d) RBDPOA, (e) RBDPOB and (f) CO with the presence of CTAB at 0.05% of Al$_2$O$_3$.

![Figure 8](image2)

**Figure 8.** Effect of Al$_2$O$_3$ on AC breakdown voltage of RBDPO and CO (a) without CTAB and (b) with CTAB.

Apparent improvements of AC breakdown voltages at 1% probability are observed with introduction of Al$_2$O$_3$ either without or with CTAB as shown in Table 6. Without CTAB, the AC breakdown voltage at 1% probability for RBDPOA and RBDPOB can increase up to 40% and 33% with 0.025% addition Al$_2$O$_3$. The highest AC breakdown voltage improvement at 1% probability for CO can be up to 7%. The introduction of CTAB further improves the AC breakdown voltage at 1% probability for RBDPOA of which the highest percentage of increment can be up to 52% with 0.05% addition of Al$_2$O$_3$. The same pattern is observed for CO whereby, the AC breakdown voltage at 1% probability increases by 15% with 0.05% addition of Al$_2$O$_3$. However, the same significant improvement effect is not found for RBDPOB where the presence of CTAB can only increases the AC breakdown voltage at 1% probability up to 15% only with 0.001% addition of Al$_2$O$_3$. 
### Table 6. AC breakdown voltage of RBDPO and CO at 1% probability at different concentration Al$_2$O$_3$.

| Samples | Volume of Concentration (%) | Breakdown Voltage at 1% Probability (kV) |
|---------|-----------------------------|------------------------------------------|
|         |                             | Without CTAB | With CTAB       |
| RBDPOA  | 0                           | 21.60        | 21.60           |
|         | 0.001                       | 23.57        | 30.75           |
|         | 0.025                       | 30.32        | 31.68           |
|         | 0.035                       | 28.50        | 32.24           |
|         | 0.05                        | 23.49        | 32.81           |
| RBDPOB  | 0                           | 25.88        | 25.88           |
|         | 0.001                       | 28.70        | 29.65           |
|         | 0.025                       | 34.35        | 25.03           |
|         | 0.035                       | 27.85        | 26.92           |
|         | 0.05                        | 23.47        | 25.99           |
| CO      | 0                           | 27.21        | 27.21           |
|         | 0.001                       | 28.10        | 20.98           |
|         | 0.025                       | 28.54        | 24.45           |
|         | 0.035                       | 29.12        | 24.05           |
|         | 0.05                        | 27.44        | 31.20           |

### 4. Discussion

Based on the study, only insulative nanoparticle, Al$_2$O$_3$ could slightly improve the average AC breakdown voltage of RBDPO and CO either without or with CTAB as shown in Figure 8. In addition, the improvement of AC breakdown voltages of the oil samples take place at no specific volume concentrations of Al$_2$O$_3$ similar as reported in Reference [43]. It is due to the agglomerations of nanoparticles in oil samples could not be controlled with the increment of volume concentration of nanoparticles which in turn lead to the difficulties to identify the optimum concentration for AC breakdown voltage improvement [8,17]. Previous study has shown that Fe$_3$O$_4$ could improve the average AC breakdown voltage of vegetable oil such as rapeseed oil, natural ester FR3 and PFAE [5,20,44]. However, the current study shows that Fe$_3$O$_4$ could not improve the average AC breakdown voltages of RBDPO and CO either without or with CTAB as shown in Figure 4. It is possibly due to differences on the chemical composition between RBDPO/CO and other types of vegetable oils. Further investigation on this aspect is needed to confirm the findings in the future. CuO has shown to be capable of improving the average AC breakdown voltage of mineral oil [45]. The current study shows that there are no improvements on the average AC breakdown voltages of RBDPO and CO either without or with CTAB as shown in Figure 6. At the moment, there is yet any study on the effect of CuO on the average AC breakdown voltage for other types of vegetable oils. Further investigation is needed to extract the knowledge of the negative effect of CuO on the average AC breakdown voltage of RBDPO and CO through extensive study at the molecular level.

Meanwhile, the effects of CTAB on the AC breakdown voltages of RBDPO and CO filled with nanoparticles under study are not clear. Previous studies have shown that CTAB is one of the most common surfactants that can be used to reduce the agglomeration and improve dispersion of the nanoparticles in mineral oil, palm oil, coconut oil and soybean ester oil [11,25,26]. Previous studies on the palm ester oil and soybean ester oil based ZnO and TiO$_2$ nanofluids show increments of AC breakdown voltages with introduction of CTAB. This is due to the fact that a charge trapping capability increases as a result of improvement of the nanoparticles aggregation [25,33]. However, the improvement of AC breakdown voltage of RBDPO based CuO nanofluid in the presence of CTAB found in Reference [33] is somehow contradictory to the current study. The repeated test in the current study reveals that the AC breakdown voltages of the oil samples further decreases as CTAB is introduced. The finding in the current study as shown in Figures 4b and 6b is in line with Reference [26], which shows that CTAB has no clear impact on the AC breakdown voltage of RBDPO based TiO$_2$ nanofluids. This is possibly due to limited compatibility of CTAB with certain nanoparticles.
and its viscosity effect. Previous study on mineral based TiO$_2$ nanofluids reveals that the attraction force between the nanoparticles and CTAB can also lead to the agglomerations among these opposite charged particles [11]. These agglomerations could initiate low charge trapping and deformation in the electric field which to a certain extent affect the AC breakdown voltage [8,11]. The high viscosities of RBDPO and CO could also cause suspension of nanoparticles which in turn lead to no apparent positive impact of CTAB on AC breakdown voltages.

Generally, the current findings show that the introduction of nanoparticles at certain volume concentrations could increase the AC breakdown voltage at 1% probability for RBDPO and CO either with or without CTAB as shown in Tables 4–6. All nanoparticles show positive impact on the AC breakdown voltage at 1% probability of RBDPO and CO at certain volume concentrations of which Al$_2$O$_3$ gives the highest improvement. From the practical point of view, the improvement of the AC breakdown voltage at the lowest probability could help to improve the design of transformers filled with vegetable-based nanofluids in the future.

5. Conclusions

The AC breakdown voltages of RBDPOA, RBDPOB and CO slightly increase with the introduction of Al$_2$O$_3$ either without or with CTAB. RBDPO and CO show clear decrement trends of average AC breakdown voltages with the introduction of Fe$_3$O$_4$ and CuO either without and with CTAB. Significant improvement of AC breakdown voltage at 1% probability is found with the introduction of Fe$_3$O$_4$, CuO and Al$_2$O$_3$ at certain volume concentrations. However, there is no clear knowledge that can be obtained on the best volume concentration of nanoparticles which can give the optimum improvement of AC breakdown voltages of RBDPO and CO. The introduction of CTAB gives improvement on the agglomeration and increases the dispersion of the nanoparticles in majority of the RBDPO and CO based on TEM imaging. However, this phenomenon has no direct effect on the AC breakdown voltages of RBDPO and CO, which implies the complexity of vegetable-based nanofluids fundamentals application in transformers.

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Nomenclature

$\alpha$ Scale parameters  
$\beta$ Shape parameters  
$t$ Measured data  
kV Kilo Voltage  
Fe$_3$O$_4$ Iron (II,III) Oxide  
Fe$_2$O$_3$ Iron (III) Oxide  
ZnO Zinc Oxide  
SiO$_2$ Silicone Oxide  
TiO$_2$ Titanium Oxide  
Al$_2$O$_3$ Aluminium Oxide  
CuO Copper (II) Oxide  
ZrO$_2$ Zirconium Dioxide  
MWCNT Multi-wall Carbon Nanotubes  
AIN Aluminium Nitride
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