ABSTRACT Alternative transformer oil has been investigated universally in the past years. Different types of vegetable oil have been proposed and evaluated as replacements for conventional transformer oil (mineral oil) due to increasing exploitation and depleting petroleum reserves. In response to growing concern about global environmental and sustainable issues, this article discusses the suitability of palm oil (PO) and palm oil-based nanofluids (PO-N) as alternative transformer oils. A brief discussion of environmental concerns is provided in this paper, and the detailed properties of PO are thoroughly addressed. The electrical performance (alternating current breakdown voltage and lightning impulse breakdown voltage), physical behaviour (viscosity, flash point, and fire point), tan delta, and relative permittivity of PO and PO-N are also discussed in this paper. Based on reliable data and research, it has been proven that refined, bleached, deodorised palm oil (RBDPO) has been determined to be the most promising type of PO when compared to others. Furthermore, when CuO nanoparticles are added to RBDPO with the use of CTAB surfactant, the AC breakdown voltage increases by 173.42 % compared to RBDPO without CuO. However, there is still scope for further improvement in nanofluid stability. In addition to these studies, future research should focus on other aspects such as ageing studies, partial discharge breakdown voltage, etc. PO has interesting properties that make the industry and scientific community take notice.

INDEX TERMS Insulation, mineral oil, nanofluid, palm oil, review, sustainable, transformer, vegetable oil.

I. INTRODUCTION The transformer is commonly used in power generation, where power is generated and raised for transmission. Transformers are also utilised at switching stations (to change the transmission voltage), distribution substations (reduce the voltage from the incoming transmission level to the distribution level), and service transformers (reduce the voltage to the utilisation level). The operational reliability and life expectancy of an electrical transformer are determined by the efficiency of insulation and the cooling behaviour of the insulator. The majority of transformers are insulated with oil (known as transformer oil) and cellulose (paper/pressboard).

Transformer oil serves as a cooling medium for the heat generated in the transformer; insulates between the windings to reduce copper losses; reduces humming noise, which causes vibration; prevents oxidation and dust; absorbs heat generated by transformer windings when energised. Many experimental and theoretical studies have also revealed that transformer oil is a consequence as well as a marker of a transformer’s health degradation [1], [2], [3].

For more than a century, a petroleum product derivative known as mineral oil (MO) has been used as transformer oil. MO refers to oils produced from dewaxed paraffin-based crude oils that are blended with additives to convey designated properties for specific purposes [4], [5], [6], [7]. Since the MO has a high flow rate and is inexpensive, it is commonly utilised in transformer applications. However,
continued use of MO may lead to oil scarcity in the future, which will be discussed in section 2.0. MO was discovered by Sebastian de Ferranti and has been used in transformers since 1891 [8]. MO is composed of straight and branched hydrocarbon molecules (paraffin, naphthene, aromatics), as shown in Fig. 1. Paraffin hydrocarbon in MO consist of methane gas (CH$_4$), normal butane (C$_4$H$_{10}$) and isobutene, while naphthene is a ring structure with six carbon atoms (within six-membered rings). Aromatic hydrocarbon, known as arene, consists of 6 configurations of carbon atoms in an aromatic compound (benzene ring) [9].

**FIGURE 1.** Hydrocarbon compounds in mineral oil.

The main reason for MO’s application as transformer oil in the power industry for decades is their satisfied identification of properties such as good electrical and dielectric properties, ageing behaviour, and low viscosity. The physical properties of MO are generally determined by their composition in terms of carbon number distribution, which is identified by the source of crude oil. As a result, these attributes vary significantly, such as boiling points, which generally range from 300°C to 600°C, and specific gravities range from 0.820 for light paraffinic base/process oils to slightly more than 1.0 for high aromatic base/process oils [10]. Furthermore, an affordable price is one of the essential criteria considered by transformer users.

However, the MO is subjected to constant oxidation and degradation because of the electric stress. Therefore, continuous inspection and maintenance of insulating oil are essential to avoid deterioration of oil properties under operational conditions and the subsequent failure of the transformer [11]. After a long time of use, the insulating oil becomes defective and is disposed of. The serviceability of insulating oil is commonly determined by prominent features such as electrical properties (dielectric strength, specific resistance, and dissipation factor), chemical properties (moisture content, acidity and sludge content) and physical properties (interfacial tension, viscosity, flash point and pour point) [12], [13], [14].

Nowadays, the transformer industry is witnessing the era of shifting from petroleum-based MO that is depleting, environmentally unfavourable and proven dangerous to vegetable oil (VO), also known as natural ester oil (NEO). Raising awareness of environmental issues has encouraged the development of renewable and biodegradable resources as a substitute for MO as insulation in transformers. Besides, the market and regulatory pressures to reduce the liability risk exposure of MO are increasing. According to the Google scholar web search engine, nearly 598 articles were published comprising the terms “vegetable oil” and “transformer”, while 765 articles were published in 2022 with the terms “natural ester oil” and “transformer”. While based on the IEEE Xplore database as shown in Fig. 2, a total of 388 and 505 articles have been published using the keywords VO and NEO for transformers from 2013 until 2022. It can be seen that until August 2022, 17 and 40 articles have been published under the keywords VO and NEO, respectively. For some reason, demand for biodegradable oil seems to go down after 2020.

**FIGURE 2.** Year-wise publication on keyword using ‘vegetable oil’ and ‘natural ester oil’ for transformer application based on IEEE Xplore database.

The majority of research has focused on VO, starting with the launch of ABB’s BIOTEMP® in 1999, which is derived from sunflower oil [15]. Furthermore, the Lion Corporation of Japan successfully developed Palm Fatty Acid Ester (PFAE) in 2008 as a substantial transformer oil [16]. The increasing amount of literature conducted with the VO has attracted growing interest in other countries to begin investigating their plant-based oils. Most VOs have higher flash points, higher fire points, and are bio-degradable compared to MO. Besides, VO is less flammable, which provides a higher fire protection classification. Palm oil (PO) is one of the VO that may be utilised for this purpose because of it has high flash and fire points, long-term ecologically friendly performance, and non-toxic qualities.

PO has recently been identified as a promising substitute for MO as transformer oil [17], [18], [19], [20], [21], [22]. Before PO is used in industry, it is necessary to test its
suitability for transformer application in terms of physical, chemical, electrical properties and others [23]. Several reviews and semi-review papers on the relevancy of VO as an insulating oil have been published in the recent past [24], [25], [26], [27], [28], [29], [30], [31], [32], [33]. Furthermore, a review on the addition of nanoparticles onto PO also has been discussed widely and comprehensively [34], [35], [36], [37], [38]. However, because the primary focus of these studies was on another VO, PO was only mentioned briefly. The South-East Asian trio of Malaysia, Indonesia, and Thailand, on the other hand, have conducted significant research on the implementation of PO as a transformer oil over the last few years.

Thus, the primary contribution of this paper is to conduct a comprehensive literature review on PO and its nanofluids to discuss their potential as green transformer oils and fill a knowledge gap in the research. The secondary objective is to examine the behaviour and capability of PO and its nanofluid as transformer oil. It is intended that this study would deliver a real sense of the literature, which is currently dominated by various forms of VO and highlights inadequacies. The first section of this paper discussed environmental concerns and briefly described the properties of PO. A comprehensive review related to electrical properties (AC breakdown voltage and lightning impulse breakdown voltage), physicochemical properties (viscosity, flash point, and fire point) and dielectric properties (dissipation factor, permittivity, and resistivity) was carried out. This paper also analyses the effects of PO after it has been dispersed with various types of nanoparticles. To assess the potential of PO as an alternative transformer oil, the electrical and physicochemical characteristics were compared with the requirements set by ASTM D6871 [39] standards. Furthermore, the current status of PO has been critically discussed. Following these extensive studies and investigations, it has been established that PO has excellent potential as an insulating liquid in transformers, despite some limitations in some areas.

A. ENVIRONMENTAL CONCERNS ON MINERAL OIL AND VEGETABLE OIL

1) BIODEGRADABILITY, TOXICITY TO HUMANS AND ECOSYSTEMS

The ability of a material to decompose after interactions with biological elements is referred to as biodegradability. The term “biodegradability” refers to the process of converting complex, potentially toxic materials into simple, common forms in which the elements carbon, hydrogen, and oxygen exist or are simply associated [10]. In terms of MO’s ecological implications, each type of crude oil or refined product has different physical properties that influence how the oil spreads and breaks down, determining the risk it poses to marine and human life, as well as the probability of it posing a threat to human and natural resources. The degree of biodegradability is tested based on the Coordinating European Council (CEC) method, which indicates that MO generally has poor biodegradability: between 0 – 40% [40]. Mercurio et al. [41] compared the biodegradability of MO and VO. They conclude that in the presence of microbes isolated from either coral reef or mangrove ecosystems, VO diminished faster than MO in oxygenated tropical marine conditions.

The distinction in the chemical nature of the molecules is associated with this characteristic. VO is esters and biocatalysts; hence, VO converts them to fatty acids easily and quickly, finally removing the carbon content. However, MO exhibits aromatic and naphthenic hydrocarbons, which are difficult for microorganisms to deteriorate. Molner et al. [42] investigated the remediation of MO polluted with soil and found that the poor rate of absorption of hydrocarbons derived from crude oil is the main reason that limits the diminishing in the environment. However, there are issues about the eco-toxicity and biodegradability of used VO. The chemistry of the substance and its ecological performance are affected by the duration of functionality, materials that come into contact with the oil, and physical conditions. Afida et al. [43] have studied the biodegradability of PO to measure its environmental friendliness and found that PO is readily biodegradable. The percentage of biodegradability reached 62.7% after 23 days, whereas the pass level was 60% within 28 days of the test. Most food production industries use fractionated PO components with saturation rates of up to 90% [44].

2) RECYCLABILITY

Nowadays, the growing demand for MO has contributed to increased waste oil production every year, with more than 24 million tonnes produced globally [11]. The MO that is no longer functional is almost entirely reclaimable and reusable. However, the presence of polychlorinated biphenyl (PCB) contamination in MO automatically eliminates the possibility of recycling. Waste MO in India comprises certain dangerous and poisonous substances that are soluble in water, which can pollute subsurface water. As a result, purifying and reusing waste MO is required to satisfy India’s fuel requirement. [45], [46]. This part of contaminated and non-recyclable insulation oil is a toxic waste, and the environmental impact is therefore significant. In Poland, oil producers (manufacturers, sellers, and importers) are required to keep records of the amount of MO put on the market and report the data to the Ministry of Environment. Spain has created an integrated oil management system led by an organisation named SIGAUS to manage all wasted oil in the country, including collection, transportation, and regeneration. Portugal, Greece, and Italy also operate in an almost identical system managed by SOGILUB, ENDIALE, and ADEME [47], [48].

Although it is reasonable that the majority of used MO gets recycled, it still has an impact on the environment and is a high-cost investment that needs to be operated with extreme caution. That is why VO is becoming more popular as a replacement for MO as a new insulating oil alternative. Palm oil (PO) is one of the options that are significantly more
ecologically beneficial due to their possible recycling value and the lack of hazardous waste disposal costs. Nevertheless, a huge amount of PO could cause an environmental issue if not properly treated before disposal and difficulty in managing the oil waste that is attributed to the large volume generated. There are, however, a few methods for converting waste PO into a valuable resource feedstock, fermentation media, or generating electricity [48], [49]. PO waste is a dependable resource due to its availability, continuity, and capability for renewable energy solutions [50].

3) FIRE SAFETY

Fire and explosion hazards pose a threat to the environment because they can contaminate soil, water, and the air (via smoke and toxic gases). Additionally, a transformer fire poses a serious hazard to industries and end-users, which can disrupt nearby facilities. Furthermore, they will cause power outages in many end-users, including hospitals, power plants, and waste management facilities, with obviously disastrous consequences. Statistical information from a major North American utility company shows a transformer probability of failure of 1.21% per year and a fire incident rate of 0.14% over 20 years [51]. According to data, 20% of transformer malfunctions in substations result in fires [52]. However, according to CIGRE research on 946 major transformer failures, 7.16% result in fires, 5.9% in explosions, and 4.25% in oil leakages [53]. Due to the expected growth in the number of distribution transformers in the coming years, as well as the elevated concern for the environment in general, it is predicted that fires in distribution transformers will generate attention from an environmental perspective. Hence, VO is a better alternative for replacing MO.

The risk of overpressure from electric arc gases is the same for both VO and MO [33], [54], but the risk of environmental pollution is substantially lower. This is due to the VO’s inherent properties, which do not ignite, do not spread fire, and do not cause pollution with the toxic fluid spill. A major power distribution company that had suffered a considerable number of fire and explosion incidents and damage decided to use VO as an insulating medium in their transformer. They discovered a measurable reduction in fire and explosion incidents, as well as a minimisation in the consequences of these incidents, as well as increased transformer availability [55]. Although VO does not eliminate the fire risk, its flash point and fire point are significantly greater than the MO’s. Insurance companies view the usage of VO as a considerable safety precaution that follows the recommendations of IEC 61936 [56] and allows for a reduction in insurance fees [57].

II. PALM OIL-HISTORICAL BACKGROUND

Palm oil (PO) is extracted from the palm fruit mesocarp with the scientific name of ‘Elaeis guineensis’. The individual fruit, which weighs between 6 gm and 20 g, is composed of the outer skin (exocarp), a pulp (mesocarp), and a nut consisting of a shell (endocarp) and the kernel. The PO originated in West Africa and was introduced to Peninsular Malaysia as an ornamental plant by the British in the 1870s. It can be harvested all year long due to its long productive life (commonly 25–30 years), ensuring a continuous PO supply [58]. The Food and Agriculture Organization of the United Nations (FAO) considers crude palm oil (CPO) and crude palm kernel oil (CPKO) to be industry-primarily products. CPO and CPKO, which are derived from mesocarp and kernel, need to undergo extensive processing before reaching the consumer, as shown in Fig. 3. The rate of oil extraction from a palm fruit bunch varies from 17 to 27% for CPO and from 4 to 10% for CPKO [59]. The main differences between CPO and CPKO are in colour, with CPO being naturally reddish-brown due to a high beta-carotene content [60]. CPO is a highly saturated vegetable fat that is semisolid at room temperature [61]. However, refined, neutralised, bleached, and deodorised CPO is a common commodity known as RBDPO and does not consist of carotenoids [62]. RBDO is the most common PO product sold in global commodity markets. Many companies fractionate it further to produce PO for cooking oil or process it into other products. These oils are used and marketed separately according to their supply and demand conditions [63]. The RBPO is often used in the food industry due to its low cost [64] and has a high oxidative stability (saturation) when used for the frying process [65], [66].

Fractionation of RBDPO separates olein and stearin. RBDPO olein primarily composed of monosaturated and disaturated triacylglycerol (TG), while RBDPO stearin is composed of disaturated and tri-saturated TG [67]. TG is a chemical compound comprised of three elements: carbon, hydrogen, and oxygen. These elements combine to form fatty acids and glycerol, as shown in Fig. 4, where R_s, R_h, and R_c reflect the hydrocarbon chain in a fatty acid molecule.
The term triacylglycerol refers to three (tri) acyl group (carboxylic acid) molecules bonded to a glycerol molecule. Glycerol is a type of alcohol with hydroxyl functional groups, whereas fatty acid is a long carbon chain. Generally, a fatty acid consists of 12–24 carbon atoms in length with an attached carboxyl group. PKO is refined, bleached, and deodorised PKO. It is also known as RBDPKO olein (liquid phase) and RBDPKO stearin (solid phase). RBDPKO olein has a higher amount of TG compared to RBDPKO stearin due to the distribution of oleic acid and linoleic acids. RBDPKO olein also contains a smaller amount of saturated acid and a high content of short-chain fatty acids [68], [69].

![General chemical composition of palm oil](image)

**FIGURE 4.** General chemical composition of palm oil.

### III. ELECTRICAL PROPERTIES OF PALM OIL AND NANOFLUID

In recent times, the focus has been on the usage of PO not only for food but as an alternative to transformer oil due to its green credentials. The Siemens company has produced the world’s first large-scale transformer that uses VO as insulation in a transformer with a voltage of 123 kV. As a result, Siemens is the first transformer company that does not require proof of water hazard classification [70]. This part provides information on the electrical breakdown properties that are associated with PO as the first step towards the replacement of petroleum-based MO for better performance and a green environment.

#### A. AC BREAKDOWN VOLTAGE

The alternating current breakdown voltage (ACBDV) is the most general and commonly utilised basic electrical test for transformer oil in high voltage environments, and it is typically performed at a nominal frequency of 50 Hz or 60 Hz. The ACBDV is measured based on ASTM D1816 [71] and IEC 60156 [72] standards. Measurements of AC BDV are mainly conducted according to two types of standards: The American Society for Testing and Materials (ASTM) and the International Electrotechnical Commission (IEC). The ASTM introduced another two standards for measuring breakdown voltage values: ASTM D1816 and ASTM D877. The main differences between them are the shapes of the electrodes, the gap between electrodes used in the experiment, and the rate of voltage rise. Table 1 presents the comparison between the three standards. Referring to the ASTM D6871 [39] and IEC 60156 [72] standard specifications for VO, insulating oil must satisfy a minimum breakdown voltage level of 30 kV to be qualified as transformer oil.

**TABLE 1.** Comparison of ASTM and IEC standards for measuring AC breakdown voltages.

| Standards       | ASTM D1816 | ASTM D877 | IEC 60156 |
|-----------------|------------|-----------|-----------|
| Description     | Most widely used standard in North America       | Older standard                          | Various countries have adopted it       |
| Shape of electrodes | Polished Brass | Brass       | Brass/Brass/Stainless Steel          |
| Diameter: 36 mm | Diameter: 25.4 mm | Thickness: ≥ 3.18 mm | Diameter: 12.5 mm – 13 mm |
| Voltage rate of rising | 2 mm/1 mm 0.5 kV/s | 2.54 mm 2.5 kV/s | 3 kV/s 2 kV/s |
| Time between breakdowns | 1 to 1.5 minutes | 1 minute | 2 minutes |
| Stirring        | Continuous with impeller (200-300 rpm)       | None                                   | Optional with a magnetic bar          |
| Breakdown value | Mean of 5 measurements                        |                                       |                                       |

1) **AC BREAKDOWN VOLTAGE OF PALM OIL**

This section focused on the research studies by scholars regarding ACBDV, where various types of PO from different countries were measured. Fig. 5 and Table 2 depict various ACBDV results of PO by various researchers that used 2.5 mm gap distances of electrodes as a benchmark. Mohd et al. [73] compared the ACBDV of RBDPO olein, RBDPKO, and CPO, where it was found that CP obtained the highest ACBDV value, followed by RBDPO olein and RBDPKO. However, experimental findings demonstrated that RBDPO olein, after being blended with oleic acid (OA), produces the highest ACBDV compared to other PO samples. The RBDPO-OA obtained a 202.67% enhancement compared to the standard recommendation (30 kV). This may be due to the excellent moisture tolerance effects of the intermolecular hydrogen bonds between water and the polar groups of RBDPO. Furthermore, OA might affect the decrement of saturated fatty acids (SFA). Ravulapalli et al. [74] reported that a higher amount of SFA imparted lower oxidative and thermal stability, which eventually leads to a faster deterioration rate. In general, PO consists of 40% of OA (mono-unsaturated fatty acid) and 45% of palmitic acid (SFA) [32].

Some studies also present experimental results of palm oil methyl ester (POME) and palm kernel oil methyl ester (PKOME), which are obtained from the transesterification process. Transesterification, known as alcoholysis, is the
reaction of a fat or oil with an alcohol (methanol or ethanol) to form esters and glycerol to reduce the viscosity of VO. Suhaimi et al. [84] found that POME has more than 60 kV ACBDV, which is the equipment’s maximum test voltage and produces higher ACBDV than RBDPO. The transesterification process enhances the dielectric integrity of the fatty acid methyl ester, which is responsible for delaying the breakdown process. Asse et al. [75] and Abdelmalik et al. [76] studied the properties of ACBDV of PKOME and figured out that both have positive results. Abdelmalik et al. also compared the performance of epoxy PKOME, PKOME with C-3 and C-4 carbon side chains. The author reported that the side-branched carbon chain did not appear to have any effect on the breakdown field. It is also reported that low viscosity and high oxidative stability caused by PKOME produce high ACBDV and are viable as alternative insulating oils for transformers.

Another type of PO known as Palm Fatty Acid Ester (PFAE) is also being studied by several researchers due to its low viscosity behaviour and 1.3 times higher dielectric constant compared to MO. It is also known to have good oxidative stability, and a railroad company in Japan has already used PFAE as an insulator in a transformer [77], [78]. Generally, PFAE is produced by synthesising fatty acid alkyl ester by the molecular design technique and the transesterification process from fatty acid methyl ester and alkyl alcohol.

From 2015-to 2017, the researchers [79], [80], [81] agreed that PFAE outperformed MO in terms of ACBDV. However, due to the unexpected performance of RBDPO, which is in great demand compared to PFAE, investigations into PFAE have recently been limited.

Yaacob and Alsaedi [82] investigate the ACBDV performance of RBDPO, RBDPO category 8 (CP8) and RBDPO category 10 (CP10). The CP10 obtained the highest ACBDV with 52.73 kV, followed by CP8 and CPO with 41.92 kV and 16.57 kV. This result is because of the amount of fatty acid contained in the oil samples, where CP8 and CP10 consist of less fatty acid than CPO. Furthermore, the fact that RBDPO with a lower content of fat showed better breakdown strength. The fat content in the RBDPO may cause oxidation which releases volatile acids and aldehydes [83]. Generally, the difference between CP8 and CP10 is the cloud point, where CP8 has a maximum of 8°C while CP10 has a maximum of 10°C temperature. Clout point refers to the lowest temperature at which long-chained paraffin begins to crystallize, causing the oil to turn cloudy. In general, low cloud points will have a lower density and a lower boiling point.

Most of the researchers were attracted to studying the behaviour of RBDPO instead of other types of PO. In 2022, Hamid et al. reported that RBDPO gained 199.63% ACBDV enhancement compared to the IEC recommendation value, while Suhaimi et al. [84] reported that 166.67% enhancement. In 2021, Faiz et al. [85] also reported a 73.63% ACBDV performance. However, in the same year, Ahmed et al. [86] reported an 18% decrement in ACBDV for RBDPO. However, extensive research from 2004–2020 agreed that RBDPO had shown the potential as a good insulator. RBDPO consists of a balance of saturated fatty acid (SFA) and unsaturated fatty acid (USFA) compared to other types of PO, which might contribute to the ACBDV results. Furthermore, RBDPO has high water solubility (moisture saturation level), which is known as hygroscopicity. Hygroscopicity is the phenomenon of absorption or adsorption of water molecules from the surrounding environment. This is due to the polar carboxyl group (COOR) ability contained in the RBDPO molecular chain structure, which participates in a hydrogen bond. Therefore, the RBDPO can dissolve much more moisture with low relative water content, hence increasing the ACBDV values.
TABLE 2. The AC breakdown voltages of various types of palm oil studied by different researchers.

| Year | Ref. No. | Types of Oil | Breakdown Voltage (kV) | Standard |
|------|----------|--------------|------------------------|----------|
| 2022 | [87]     | RBPDO        | 89.8                   | IEC 60156 |
| 2022*| [84]     | RBPDO        | 80                     | IEC 60156 |
| 2022 | [75]     | PKOME        | 57.5                   | ASTM D1816 |
| 2021 | [85]     | RBPDO        | 52.09                  | IEC 60156 |
| 2021 | [88]     | RBPDO        | 56.15                  | IEC 60156 |
| 2021 | [73]     | RBPDOKO      | 40.90                  | ASTM D1816 |
|      |          | CPO          | 29.1                   | ASTM D1816 |
|      |          | RBPDO - CPO  | 78.1                   | ASTM D1816 |
|      |          | RBPDO - caprylic acid | 78.1 | ASTM D1816 |
|      |          | RBPDO - oleic acid | 78.1 | ASTM D1816 |
|      |          | RBPDO - methyl laurate | 72.8 | ASTM D1816 |
|      |          | RBPDO - methyl palmitate | 81.2 | ASTM D1816 |
|      |          | RBPDO - myristate | 62.1 | ASTM D1816 |
|      |          | RBPDO - isopropyl myristate | 78.1 | ASTM D1816 |
| 2021 | [89]     | PKO          | 70.7                   | IEC 60156 |
| 2021 | [90]     | PKOME        | 45.91                  | ASTM D1816 |
| 2021 | [86]     | RBPDO        | 24.6                   | ASTM D1816 |
| 2019*| [91]     | RBPDO        | 39.5                   | IEC 60156 |
| 2019 | [92]     | PO           | 48.50                  | IEC 60156 |
| 2019 | [93]     | RBPDOKO      | 59.4                   | IEC 60156 |
| 2018 | [94]     | PO           | 48.50                  | IEC 60156 |
| 2018 | [95]     | POME         | 60                     | IEC 60156 |
|      |          | CPKO         | 39.8                   | IEC 60156 |
|      |          | PO Stearin   | 19.3                   | IEC 60156 |
| 2018 | [96]     | PO           | 77.12                  | IEC 60156 |
| 2018 | [97]     | RBPDO        | 76.17                  | IEC 60156 |
| 2018 | [98]     | RBPDO        | 32.65                  | IEC 60156 |
| 2018 | [99]     | PKOME epoxy  | 42.58                  | ASTM D1816 |
| 2017 | [100]    | RBPDO        | 80.062                 | ASTM D1816 |
| 2017 | [79]     | PFAE         | 68.75                  | ASTM D1816 |
| 2017 | [101]    | RBPDO        | 46.72                  | ASTM D1816 |
| 2016 | [80]     | PFAE         | 64.10                  | ASTM D1816 |
| 2016*| [102]    | RBPDO        | 82                     | IEC 60156 |
| 2015 | [17]     | RBPDO        | 84.23                  | ASTM D1816 |
| 2015 | [103]    | RBPDO        | 42.5                   | ASTM D1816 |
| 2015 | [81]     | PFAE         | 38.43                  | IEC 60156 |
| 2015 | [82]     | RPO          | 40.35                  | BS 148   |
| 2014 | [20]     | CPO          | 16.57                  | BS 148   |
|      |          | CPS          | 41.92                  | ASTM D1816 |
|      |          | CP10         | 52.73                  | ASTM D1816 |
|      |          | RBPDO Olein  | 45.25                 | ASTM D1816 |
| 2014 | [104]    | RBPDO Olein  | 94                    | ASTM D1816 |
| 2011 | [105]    | PKOAE        | 106.5                  | ASTM D1816 |
| 2011 | [76]     | PKO          | 101.5                  | ASTM D1816 |
|      |          | PKOME        | 105.5                  | ASTM D1816 |
|      |          | PKOME epoxy  | 106.5                  | ASTM D1816 |
|      |          | PKOME + C3   | 105.6                  | ASTM D1816 |
|      |          | PKOME + C4   | 105.25                 | ASTM D1816 |
| 2011 | [106]    | RBPDO Olein  | 45                    | ASTM D1816 |
| 2009 | [107]    | RBPDO Olein  | 57                    | ASTM D1816 |
| 2008 | [77]     | PFAE         | 81                     | IEC 60156 |
| 2008*| [108]    | PO           | 37                     | IEC 156/ ASTM D877 |

2) AC BREAKDOWN VOLTAGE OF PALM OIL-BASED NANOFLUID

The application fields of nanoparticles are expanding as nanotechnology advances. Nanoparticles have unique mechanical, electrical, and thermal properties, strong chemical activity due to their nano-sized effects; and many other interesting attributes. Studies have proceeded to further hybridise PO with different types of nanoparticles. The method of using nanoparticles (NP) involves a suspension procedure to produce a stable nanofluid (NF). The NP that is involved in most of the studies includes Multi-walled Carbon Nanotube (MWCNT), Graphene, Silicon Carbide (SiC), Aluminium Oxide (Al2O3), Titanium Dioxide (TiO2), Silicon Dioxide (SiO2), Zinc Oxide (ZnO), Barium Titanate (BaTiO3), Zirconium Dioxide (ZrO2), Iron (III) Oxide (Fe3O4), and Copper Oxide (CuO).

There are two common methods for preparing NF; the one-step method and the two-step method. One-step method synthesis of NP into the PO at the same time processes physical vapour condensation to minimise agglomeration and enhance uniform particle distribution. However, this method is expensive and cannot be performed on a large scale. For the two-step method, the initial stage involves a physical and chemical method of synthesising dried NP. Then, the NP is dispersed into an oil sample aided by a sonication process, magnetic stirring, ball milling process, or high shear mixing [110]. This process has several steps, which raises the probability of agglomeration. However, the production cost is relatively lower and can be produced on a large scale. As a result, various researchers prefer this approach compared to the one-step method.

Surfactants of various types are commonly used to prevent agglomeration or sedimentation in nano-oil samples while also improving their stability. Oleic Acid (OA) is normally utilised as a surfactant and other surfactants such as Sulphanate, Stearic Acid, Propylene Glycol, Span80, Sodium Dodecyl Sulphate (SDS) and Sorbitan Monooleate have also been used to increase the stability of NF [111], [112]. Surfactant has the ability to alter the physical properties of NF and improve the electrostatic and steric abilities of insulating oil. However, the synthesis of NP with PO with the aid of surfactant has very limited literature.

Nor et al. [113] investigated the influence of Cetrimonium Bromide (CTAB) in TiO2-PO on ACBDV, LIBDV...
performance, tan delta, permittivity, and resistivity properties and discovered that there was no clear improvement pattern. Mohamad et al. [91] compared the ACBDV of Fe$_3$O$_4$-RBDPO, Al$_2$O$_3$-RBDPO, and CuO-RBDPO with and without the aid of CTAB surfactant. The introduction of CTAB gives an improvement in the agglomeration based on the Transmission Electron Microscope (TEM). In another study [22], the author also compared the influence of different surfactants (OA, SDS, and CTAB) on Al$_2$O$_3$-RBDPO NF. It has been discovered that SDS and OA exhibit a larger particle size distribution than CTAB surfactant, which promotes agglomeration in oil samples. The CTAB adsorbed on the surface of Al$_2$O$_3$ stabilises the overall charge neutrality, resulting in the formation of an electrical double layer that creates mutual repulsion and provides dispersion stability. Regardless of surfactant type, a suitable surfactant-NP ratio must be investigated further to avoid sedimentation and agglomeration for a longer period of time. Furthermore, the types of PO are an essential part in determining the best alternative transformer oil.

This subsection focuses on the ACBDV performance of palm oil-based nanofluid (PO-NF) as an alternative to biodegradable transformer oil. The data from the literature is extracted, and the results are analysed and summarised in Fig. 7 and Table 3.

**a: MULTI-WALLED CARBON NANOTUBE**

The discovery of Multi-walled Carbon Nanotube (MWCNT), which are elongated hollow cylindrical structures made up of a few graphene sheets, has piqued the curiosity of researchers from a variety of industries. Several researchers have shown that dispersing MWCNT in MO improves ACBDV performance [114], [115], [116], [117]. The process of electrons hopping in traps and releasing electrons in a delocalized state is associated with the mechanism of insulation breakdown. Due to this repeating trapping and de-trapping process, the fast electron will be transformed into a slower electron while going from a high electric field zone to a low field region [114]. The most current work, published in 2022, involves the suspension of MWCNT in RBDPO to assess the performance of ACBDV. Suhaimi et al. [84] reported that increasing the concentration of MWCNT from 0.0125 g/L to 0.5 g/L caused the ACBDV pattern to decrease to 22.30 kV from 80 kV (pure RBDPO). Another study [97] also has similar concerns where after dispersing 0.01 g/L, 0.05 g/L and 0.2 g/L, the ACBDV of RBDPO decreased to $-20.90\%$, $-25.65\%$ and $-61.26\%$, respectively. The presence of MWCNT may be incompatible with RBDPO, which has a complex chemical structure and is a highly entangled product. Furthermore, no research has been conducted on the dispersion of MWCNT-PO with the assistance of a surfactant. Surfactant compounds work by reducing the surface tension between the base fluid and the NP to aid in the suspension process. One thing that affects the stability of a nanofluid is how it is suspended, which depends on the material [118].

**b: GRAPHENE**

Graphene is extracted from graphite and is entirely composed of carbon atoms and perfectly distributed in a hexagonal honeycomb [119]. Wajanasoonthorn and Sukrs [88] investigated the ACBDV of RBDPO and POME with nanographene NP. Pure RBDPO and POME have been found to obtain higher ACBDV at all weight percentages of graphene (0.0012 wt% to 0.01 wt%). The author suggested that as the electric field increases, graphene polarises, resulting in positive and negative charges being generated at the NP. The dipole-dipole interactions between particles caused by these charges will speed up the agglomeration process. As a result, they create an electrical bridge or short circuit between the electrodes. However, when the ACBDV of RBDPO-graphene and POME-graphene are compared, it seems that POME-graphene is faster to breakdown owing to its reduced viscosity qualities. In fact, POME is produced by the transesterification process to reduce the viscosity properties.

**c: TITANIUM DIOXIDE**

Titanium dioxide (TiO$_2$) or known as Titania, is considered to be one of the three most-produced NPs, along with SiO$_2$ and ZnO [120]. It is a naturally occurring mineral existing in several crystalline forms (rutile and anatase). TiO$_2$ is among the most widely used materials added to improve the ACBDV of various insulating oils. Several researchers studied the effect of ACBDV on RBDPO with TiO$_2$, while some of them studied the ACBDV effect of TiO$_2$ on PKO, POME, and PFAE. However, it is interesting that all of the studies gained quite an enhancement on ACBDV. In 2021, Muang-pratoom [121] found that after adding TiO$_2$, the ACBDV performance was enhanced by as much as 23.29%, while in 2017, Nor et al. [113] reported a 15.56% increment after adding TiO$_2$ and a 13.70% increment after dispersing TiO$_2$ along with Cetrimonium Bromide (CTAB) surfactant. It is observed that the ACBDV tends to decrease after adding CTAB surfactant, even though the NF sample becomes more stable and less agglomerate.

RBDPO is known to have a low melting liquid fraction of natural ester, which contains 48% Oleic Acid (OA) due to refining and bleaching processes. Because OA is a natural surfactant, CTAB surfactant may not be appropriate for dispersing TiO$_2$ in this case. In addition, Makmud et al. [122] studied TiO$_2$ suspended in RBDPO with concentrations in the range of 0.01 g/L, 0.1 g/L, and 1.0 g/L without surfactant. The ACBDV measured by ASTM D1816 standard of RBDPO with TiO$_2$ gain 12.90% 48.39% and 67.74% enhancement at 0.01 g/L, 0.1 g/L and 1.0 g/L. The author gives an opinion that mechanically-stable NF is obtained when OA is chemisorbed as a carboxylate on the NP surface. Consequently, the interfacial zone of NF as the solid-liquid suspension is enhanced.

According to the Van Der Waal theorem, the interfacial zone in NF is to construct intermolecular forces that keep the molecules apart. As a result, the NP is difficult to polarize, trapping charges and slowing down the electron mobility. Furthermore, it is noticed that as the concentration of
TiO₂ increases, the ACBDV also increases. TiO₂ is a semi-conductive NP; hence, reduction and overlapping interfacial zone space do not affect the dielectric response compared to highly-conductive NP. The author also simulated the magnitude of surface current density between highly-conductive NP (Fe₂O₃) and semi-conductive NP (TiO₂), as shown in Fig. 6. It can be seen that TiO₂ has a lower magnitude of current density than Fe₂O₃, which makes TiO₂ initiate breakdown slower than Fe₂O₃ at a similar concentration. Saenkhumwong and Sukari [123] also conclude that increasing the weight concentration of TiO₂-POME from 0.01 g/L to 0.20 g/L results in a higher trend of ACBDV. According to the author, the electrons were attracted and trapped in the gaps between TiO₂ NP, causing ACBDV to increase. Not only does TiO₂-RBDPO produce positive results, but PKO-TiO₂ and PFAE-TiO₂ also produce significant enhancements of up to 32% and 29.71%, respectively [79], [90]. It can be stated that the chemical structure of PO is compatible with TiO₂ NP.

**FIGURE 6.** The electric displacement field and current density distributions of (a) Fe₂O₃ and (b) TiO₂ using Finite Element Analysis (FEA) [118].

d: IRON OXIDE

Iron (II, III) Oxide is written as FeO/ Fe₂O₃ (black powder), and Iron (III) Oxide is written as Fe₂O₃ (red powder). These are oxides of iron that have iron atoms in different oxidation states. Fe₂O₃ is a mixed oxide where Fe is present in both +2 and +3 oxidation states, while Fe₂O₃ is a simple oxide where Fe is only in the +3 oxidation state. Most researchers are interested in the suspension of Fe₂O₃, where Mohamad et al. [79], [80] reported 45.16% and 41.61% enhancement of ACBDV at 0.01 g/L weight concentration of Fe₂O₃ with the aid of OA compared to pure PFAE. The improvement is considered to be due to the electron scavenger action of Fe₂O₃ NP. This means that fast electrons are converted into slow, negatively charged electrons, and the streamer process takes longer to breakdown. In 2019, Mohamad et al. [91] compared pure RBDPO, RBDPO-Fe₂O₃, and RBDPO-Fe₂O₃ synthesis with CTAB. In brief, the introduction of Fe₂O₃ reduced the ACBDV performance by about 8.86% (without CTAB) and 3.8% (with CTAB). Previous research has shown that adding Fe₂O₃ to other types of VO improves ACBDV significantly, which contradicts RBDPO-Fe₂O₃. Because of the complex composition of RBDPO, Fe₂O₃ NP may be difficult to chemisorb with RBDPO molecules. However, Makmud et al. [122] reported a 22.58% enhancement in ACBDV after adding Fe₂O₃ with RBDPO. This might be due to Fe₂O₃’s having higher electrical conductivity, which is 10⁶ times higher than Fe₂O₃. Besides, a study also reported that Fe₂O₃ has high agglomeration due to high saturation magnetization properties compared to Fe₂O₃. This made it hard to control the dispersion degree of NO, which limited the use of NF [124].

e: ALUMINIUM OXIDE

Aluminium oxide (Al₂O₃), also known as alumina, is a non-conducting or insulating NP. Al₂O₃ possesses exceptional impact resistance, chemical resistance, high-temperature properties, and mechanical properties. Al₂O₃ is less expensive than other types of NP. In 2021, Oparanti et al. [90] synthesised Al₂O₃ (0.2 wt% to 1 wt%) with PKOME to analyse the breakdown strength behaviour. The ACBDV performance of PKOME-Al₂O₃ increased from 0.2 wt% to 0.6 wt% before gradually decreasing. PKOME-Al₂O₃ at 0.2, 0.4, and 0.6 wt% improves ACBDV by up to 50.93%, 63.53%, and 80.17% when compared to pure PKOME. The increment of ACBDV may be due to the non-conducting properties of Al₂O₃, which consists of more shallow traps than semi-conductive NP (ZnO, CdS, TiO₂) and conductive NP (Gold, Fe₂O₃, Fe₃O₄). Through a trapping and de-trapping mechanism, the shallow trap aids in the conversion of fast electrons to slower electrons produced by a high electric field. Eventually, the reduction after 0.6 wt% may be caused by a decrease in the inter-particle distance, which affects the decrement in breakdown strength. According to Chen et al. [125], increasing the concentration of NP beyond a certain amount demonstrates the implication of a tunnelling/bridging mechanism, which results in lower breakdown voltages. In this case, layers adjacent to NP act as conductors in a very high electric field. Mohamad et al. [91] in 2019 investigated the effect of CTAB surfactant on RBDPO-Al₂O₃ NF. The ACBDV of RBDPO-Al₂O₃ improved by 6.82% after synthesis with CTAB and 56.67% improvement compared to the standard recommendation (30kV). In 2017, Mohamad et al. [79] suspended Al₂O₃ in PFAE oil with the aid of OA as a surfactant. Based on the Weibull probability of 63.2% (lifetime breakdown estimation), the ACBDV of PFAE-Al₂O₃ indicates 92.18 kV compared to pure PFAE, where the ACBDV is 68.75 kV for a 2.5 mm gap distance between electrodes. In brief, Al₂O₃, with or without surfactant, produces better insulation breakdown properties for a few types of PO (PKOME, RBDPO, and PFAE).

f: COPPER OXIDE

Copper Oxide (CuO) is a semi-conductive material that exhibits high-temperature superconductivity, is relatively cheap, and can be easily mixed with polarised liquid. According to some studies [126], CuO NP has the ability to reduce the average and maximum temperature of MO, resulting in an improvement in transformer thermal performance. Furthermore, some studies have shown that CuO is a better
alternative transformer oil than other compound oxides [127], [128]. Mohamad et al. [91] compared the ACBDV performance of RBDPO after being dispersed with CuO NP with and without the aid of CTAB surfactant. If referring to the TEM image of RBDPO-CuO, the agglomeration is decreased after adding CTAB at 0.05% volume concentration. However, the results of ACBDV contradict the theory, where the ACBDV is further reduced as CTAB is introduced by as much as −74.68%. Besides, without CTAB, the ACBDV of RBDPO-CuO decreased to −24.05% compared to the pure RBDPO. The findings contradict the findings of Mohamad et al. [129], who found that the ACBDV of RBDPO-CuO with the aid of CTAB surfactant produced a 173.42% enhancement over pure RBDPO. Furthermore, RBDPO-CuO with CTAB gains the highest performance compared to RBDPO-CuO with the aid of Sodium-dodecyl Sulfate (SDS) (33.54% enhancement) and OA (149.37%) surfactant. Differences in results could be caused by the size of the sample, methodological approaches, or the setting of the experiment.

**g: ZINC OXIDE**

Zinc Oxide (ZnO) is a wide-bandgap conductive NP with high electron mobility. Several studies have found that ZnO improves the ACBDV of MO [130], [131], [132] and VO. In 2021, Muangpratoom [121] studied the ACBDV of ZnO in RBDPO and obtained a 28.71% enhancement compared to the pure RBDPO. Hussin et al. [133] also investigated the performance of ACBDV of ZnO in pure PO at 0.0015 g/L, 0.0025 g/L and 0.005 g/L without any additive or surfactant. The author used different sonication periods for each concentration in the synthesis process. The highest ACBDV value is at 0.005 g/L with 69.28 kV compared to pure PO with 38.09 kV. There is also a study on the dispersion of ZnO with other types of PO (PKOME), which is obtained from the extraction, degumming, and transesterification process of CPKO [134]. Three concentrations are taken into account (0.10%, 0.15%, and 0.20%), and it is found that as the percentage of NP increased, the ACBDV results also increased from 45.1 kV to 52.98 kV. In 2017, Saenkhumwong and Sukseri [123] investigated the ACBDV of ZnO-POME with CTAB surfactant as a stabiliser agent. A total of five concentrations (0.01 g/L – 0.20 g/L) were tested, and it is figured that a similar trend is observed, where the addition of ZnO causes an improvement in ACBDV. Low permittivity and high conductivity directly correlate to a short relaxation time constant in ZnO. Short relaxation time constants can rapidly capture fast electrons and slow the propagation of streamers in oil.

**h: SILICON CARBIDE**

Silicon Carbide (SiC) NP is a non-oxide ceramic engineering material is composed of four Carbon atoms encircling a Silicon atom [135]. SiC has very high chemical bonding properties and a high strength-to-weight ratio. In 2021, Faiz et al. [85] investigated the ACBDV effect of RBDPO with SiC. It is found that as the weight concentration of SiC increased, the ACBDV decreased gradually from 52.09 kV (pure RBDPO) to 45.3 kV (0.001 g/L), 43.2 kV (0.003 g/L), and 40.1 kV (0.005 g/L), respectively. Although the service temperature of SiC is approximately 1650°C which is very high when compared to other types of NP [136], the breakdown strength after mixing with RBDPO is quite low. Due to its low electrical conductivity (1 × 10² S/m), SiC is incapable of enhancing dielectric characteristics. Despite the fact that the SiC relaxation time constant is shorter than the streamer propagation time, there appears to be a constraint when dispersing using RBDPO.

**i: BARIUM TITANATE**

Barium Titanate (BaTiO₃) is considered one of the candidates for a high dielectric insulator. The dielectric constant of BaTiO₃ is 100 times higher than that of SiO₂ NP [137], Muangpratoom [121] conducted an experiment on RBDPO that contains BaTiO₃ at increasing temperatures (35°C – 90°C). The ACBDV improved by 0.01 vol% and 0.03 vol% as the temperature increased. The increase in ACBDV is the result of a stable suspension of RBDPO-BaTiO₃ NP. This means that BaTiO₃ NP is able to trap electrons in the oil sample due to the polarisation effect caused by NP. Besides, RBDPO-BaTiO₃ produced 2.12% (0.01 vol%) and 16% (0.03 vol%) enhancement of ACBDV compared to the pure RBDPO at normal temperature.

**j: SILICON DIOXIDE**

Another type of NP used to modify ACBDV of insulating oil is Silicon Dioxide (SiO₂), also known as Silica. SiO₂ is a compound of Silicon and Oxygen that is linked by the covalent bond. Many studies showed promising results after adding SiO₂ to MO [138], [139] and VO [140]. As a result, Yahya and Amirrazli [98] were motivated to test the influence of SiO₂ on RBDPO by referring to the IEC 60156 standard. In contrast, the ACBDV of RBDPO-SiO₂ is reduced by −21.47% when compared to pure RBDPO. However, this phenomenon is still interrupted by several factors, such as limited studies, insufficiency of suspension methods, and a shortage of theoretical understanding of the mechanism between SiO₂ and RBDPO.

**k: ZIRCONIUM DIOXIDE**

Zirconium Dioxide (ZrO₂) is available in many forms; nanodots, nanofluids, and nanocrystals. ZrO₂ consists of high chemical stability, excellent corrosion-resisting materials, and is an important dielectric material [141]. In one article, it is reported that ZrO₂ NP can be an effective agent for enhanced oil recovery [142]. The ACBDV of transformer oil with ZrO₂ suspension was studied by Pugazhendi [143] at various mass concentrations. The results showed the maximum increased at 0.01 wt% with 23% enhancement, and the ACBDV began to decrease after 0.01 wt%. In 2022, Vaishnav et al. [144] also reported that the ACBDV of ZrO₂ NF increased up to a certain concentration, which is
0.2 g/L in the case of transformer oil. For PO-based oil, Hussin et al. [133] studied the ACBDV performance of PO-ZrO$_2$ at three different concentrations. It is figured out that the highest ACBDV is obtained at 1.5 mg/L (82.65% enhancement), followed by 2.5 mg/L (79.08% enhancement), and 5 mg/L (77.26% enhancement). The difference in ACBDV between each concentration is slightly small, which is different from other studies.

The ‘charge trapping mechanism’ proposed by Hwang et al [145] explains the enhancement in ACBDV due to the addition of ZrO$_2$ NP. The polarised NP within the oil will strive to capture or trap the electron, reducing charge carrier mobility. As a consequence, the average kinetic energy of the NP in the oil decreases, hence increasing the ACBDV performance. The charge trapping is determined by the relaxation time constant ($\tau_r$), which is defined as the time required for the NP to capture (trap) and loosen up (release) the charge. The relaxation time ($\tau_r$) is denoted by (1) [145]:

$$\tau_r = \frac{2\varepsilon_1 + \varepsilon_2}{2\sigma_1 + \sigma_2}$$

where $\sigma_1$ and $\sigma_2$ are electrical conductivities of base fluid and nanoparticles, respectively, and $\varepsilon_1$ and $\varepsilon_2$ are the relative permittivity of the PO and NP, respectively. As a result, the relaxation time is affected by the relative permittivity and electrical conductivity of both the NP and PO. The addition of ZrO$_2$ increases the relaxation time, which improves the dielectric strength of the oil.

B. LIGHTNING IMPULSE BREAKDOWN VOLTAGES

Voltage transformers are built for decades-long operation in the electric power system. The failure of transformers in service could be very costly to utilities; therefore, the evaluation of dielectric performance under lightning impulse breakdown voltage (LIBDV) is important. The purpose of the LIBDV test is to secure the insulation that can withstand the lightning overvoltage occurrences in transmission lines, insulator breakdown events and the end turns of the transformer connected to the line. There are two types of charges that exist in LIBDV; positively charged and negatively charged. Nearly 95% of lightning strikes carry a negative charge, while positive lightning accounts for less than 5% of all strikes. Positive lightning is relatively rare but produces a billion Volts with 300,000 Amperes compared to negative lightning, which is 300 million Volts with 30,000 Amperes of electricity.

Measurement procedures of LIBDV are described in detail by two standards; ASTM D3300 [146] and IEC 60897 [147], for LIBDV tests by American and Europe industries, respectively. The differences between both standards are summarised in Table 4. The LIBDV test is generally measured using a standard lightning impulse voltage of 1.2/50 $\mu$s in a needle-sphere combination of electrodes with a 25 mm gap. Some studies used the needle-sphere electrode configuration, whereas others used needle-plane electrodes or sphere-sphere electrodes in their studies. The flow rate of streamer propagation in the oil is strongly influenced by the polarity and peak amplitude of the applied voltage [148]. The present section is an initiative to compare the LIBDV’s behaviour toward PO.

1) LIGHTNING IMPULSE BREAKDOWN VOLTAGE OF PALM OIL

In recent years, many publications have shown that there have been efforts to replace the conventional MO with PO. However, only a few researchers studied RBDPO types of oil for LIBDV testing. There is no information available on LIBDV testing on PFAE, POME, PKOME, or other types of PO. Fig. 9 illustrates the range of positive and negative LIBDV enhancement of PO compared to MO studied from 2014 to 2021. Table 6 lists the information on LIBDV studied by various researchers. All researchers relied on the IEC 60897 [147] standard for determining LIBDV. It is evident that all researchers also agreed that there was no improvement
observed for both positive and negative LIBDV compared to MO. Nonetheless, there have been some studies on the effects of electrode geometry, gap distances, and testing methods on LIBDV results.

Katim et al. [3] studied the LIBDV of RBDPO Olein in a quasi-uniform electric field (sphere-sphere electrodes) for both positive and negative polarity. The LIBDV results for both polarities are reduced by \(-13.04\%\) (3.8 mm gap distance) and \(-10.19\%\) (2.0 mm gap distance) for the positive charge, while for the negative charge, there is \(-12.8\%\) (3.8 mm gap distance) and \(-5.77\%\) (2.0 mm gap distance) decrements compared to the MO sample. The authors also compared three different testing methods (rising voltage, up-and-down, and multiple levels) at negative polarity with a 3.8 mm gap distance between electrodes. The difference between these three methods is described in Table 5 and Fig. 8 illustrates the sketch of the methodology for LIBDV testing. From previous studies, regardless of the test method, RBDPO Olein seemed to have lower LIBDV results than MO. This finding is similar to that of Thien et al. [149], who compared two different LIBDV testing methods (rising and up-and-down) at two gap distances (3.8 mm and 6.0 mm). Because the difference between MO and RBDPO is less than 10%, the author stated that the testing method does not have a big effect on the LIBDV of MO and RBDPO.

### TABLE 3. The AC breakdown voltages of various types of palm oil-based nanofluid studied by different researchers.

| Year | Ref. No. | Types of Oil | Nanoparticles | Surfactant | Breakdown Voltage (kV) | Standard |
|------|----------|--------------|---------------|------------|------------------------|-----------|
| 2022 | [84]*   | RBDPO        | MWCNT         | -          | 65                     | IEC 60156 |
| 2021 | [85]     | RBDPO        | SiC           |            | 45.30                  | IEC 60156 |
| 2021 | [88]     | RBDPO        | Graphene      |            | 51.83                  | IEC 60156 |
| 2021 | [90]     | PKOME        | Al2O3         |            | 64.07                  | ASTM D1816|
| 2021 | [121]    | RBDPO        | ZnO           |            | 54.7                   | IEC 60156 |
| 2021 | [133]    | PKOME        | ZnO           |            | 69.28                  | ASTM D1816|
| 2019 | [91]*    | RBDPO        | Fe2O3         | CTAB       | 36                     | IEC 60156 |
| 2018 | [96]     | PO            | MWCNT         |            | 61                     | ASTM D1816|
| 2018 | [129]    | RBDPO        | CuO           | SDS        | 52.75                  | ASTM D1816|
| 2018 | [122]    | RBDPO        | TiO2          | OA         | 98.5                   | ASTM D1816|
| 2017 | [113]    | RBDPO        | Fe2O3         | CTAB       | 95                     | ASTM D1816|
| 2017 | [123]    | POME          | TiO2          | CTAB       | 46.8                   | ASTM D1816|
| 2017 | [79]     | PFAE          | ZnO           | CTAB       | 34.12                  | ASTM D1816|
| 2016 | [80]     | PFAE          | Fe2O3         | OA         | 99.8                   | ASTM D1816|
| 2015 | [103]    | RBDPO        | TiO2          | OA         | 90.77                  | ASTM D1816|

### TABLE 4. Comparison of ASTM and IEC standards for measuring lightning impulse breakdown voltages.

| Standards | ASTMD3300 | IEC 60897 |
|-----------|-----------|-----------|
| Shape of electrodes | Steel/ Brass | Steel |
| Electrode material | Steel/ Brass | Steel |
| Electrode gap | 25.4 mm for point-sphere | 10-25 mm |
| 3.8 mm for sphere-sphere |
| Voltage increasing method | Step by step: | Step by step: |
| 3 shots per step | 1 shot per step |
| Time between breakdowns | Minimum 30s | Minimum 60s |

**FIGURE 8. Sketch of methodology for lightning impulse test.**

Thien et al. [150] investigated the influence of electrode geometry on the LIBDV of RBDPO at positive and negative polarity. Non-uniform field tests were conducted using needle-plane and needle-sphere electrodes. It was discovered that compared to needle-sphere geometry, which has a more divergent electric field, needle-plane geometry generates a lower LIBDV value. Furthermore, LIBDV appears to have
a lower value than MO in both negative and positive polarity. In general, the polarity effect of the LIBDV is influenced by the space charge and chemical structure of RBDPO and MO. The electric field strength at the head of the propagation channel varies with electrode geometry, influencing the propagation velocity [151].

MO is a non-polar medium that is difficult to separate into ions, whereas PO is a polar medium. PO also contains more ion pairs than MO. During the process of breakdown, these ions are less stable than molecules and easier to release electrons, consequently strengthening the process of collision ionisation and reducing breakdown voltage. Therefore, the negative impulse breakdown voltages of PO are lower than MO. Under the action of the external electric field, the activation energy of ion-pair dissociation decreases with the increase of field strength, as described by the Poole–Frenkel effect. The effect is shown in (2) and (3). It can be seen from (2) and (3), that with the increase of the electric field, the potential energy of ion dissociation will decrease, and more ions will be found in ester oil. Thus, the difference in the breakdown voltages between ester liquids and MO increases [152], [153].

\[
 n_0 = \sqrt{\frac{N_0 V_0}{\xi}} e^{-\frac{(u_0 - u_0')}{kT}} \quad \text{(2)}
\]

\[
 \Delta n_0 = \sqrt{\frac{q^2 E}{\pi \varepsilon_0 \varepsilon_r}} \quad \text{(3)}
\]

where
- \( n_0 \): ion concentration
- \( N_0 \): number of ions
- \( V_0 \): applied voltage
- \( \xi \): composite coefficient of ions
- \( u_0 \): activation energy of ion pairs dissociation
- \( k \): Boltzmann constant
- \( T \): absolute temperature
- \( q \): charge of ions
- \( E \): electric field strength
- \( \varepsilon_0 \): permittivity of vacuum
- \( \varepsilon_r \): relative permittivity

### TABLE 5. Comparison of lightning impulse testing methods.

| Impulse testing method | Rising Voltage Method | Up-and-Down Method | Multiple Level Method |
|------------------------|-----------------------|--------------------|----------------------|
| Description            | - Can be performed under AC and impulse conditions. - IEC 60897 and ASTM D3300 adopt this method. | - Estimate breakdown voltage at 50% probability when the breakdown voltage is normally distributed. - Save testing time | - Known as constant-voltage method. - Classic method of determining the probability of breakdown voltage. |
| Procedure              | From a certain initial voltage, the applied voltage was increased at a constant rate until breakdown occurred. The applied voltage is then reduced, and the process is repeated. | The initial voltage is set and gradually increased in a fixed step voltage pattern until the first breakdown occurs. The voltage is then reduced at the same fixed-step voltage until there is no breakdown. | Apply a certain number of shots at different voltage levels. |
| Time interval          | 60                    | 60                 | 60                   |
| between each breakdown  | 15                    | 30                 | 20                   |
| Total breakdown        |                      |                    |                      |
| measurement            |                      |                    |                      |

2) LIGHTNING IMPULSE BREAKDOWN VOLTAGE OF PALM OIL-BASED NANOFLUID

The LIBDV behaviour of mineral oil-based nanofluid (MO-NF) and VO is enhanced with distinct forms of NP. Shill et al. [159] showed that adding SiO\(_2\) NP at a concentration of 0.5% improved MO LIBDV by 25%. Hessin et al. [160] discovered that adding Mn\(_0\).2Ni\(_0\).8Fe\(_2\)O\(_4\) to MO increased LIBDV by 40%. Furthermore, Potivejkul et al. [161] investigated the effect of negative LIBDV of VO after adding TiO\(_2\) and ZnO NP and found a 14% and 21% increment, respectively. As for PO-NF, Nor et al. [113] examined the LIBDV test on RBDPO based semi-conductive NP known as TiO\(_2\) at 0.001%, 0.025%, 0.035%, and 0.05% concentrations. The oil samples are tested with and without CTAB surfactant. The LIBDV test was carried out by referring to IEC 60897 under non-uniform field, needle-sphere electrodes with a 25 mm gap distance and quasi-uniform, needle-sphere electrodes with a 3.8 mm gap distance. For the non-uniform field, the LIBDV of RBDPO-TiO\(_2\) increased by 9.2% at 0.05% concentration without CTAB, and increased by 5.9% with the addition of CTAB, respectively. While for the quasi-uniform field, the RBDPO-TiO\(_2\) is has a -2.4% lower LIBDV than pure RBDPO at 0.05% concentration with the presence of CTAB. Without the introduction of CTAB, the RBDPO-TiO\(_2\) improved by 9.0% at the same concentration. It can be concluded that the presence of CTAB does not have an obvious impact on NF in both non-uniform and quasi-uniform fields.

In 2020, Mohamad et al. [22] studied positive and negative LIBDV of RBDPO-Al\(_2\)O\(_3\) with three different surfactants; cetyltrimethylammonium bromide (CTAB), sodium dodecyl sulphate (SDS), and oleic acid (OA). The LIBDV measurement was carried out according to IEC 60897 [147] under a non-uniform field (point-sphere electrodes) with a 25 mm gap distance. According to the author, RBDPO-Al\(_2\)O\(_3\) shows significant performance under both positive and negative polarity. When the positive LIBDV is applied, high mobility electrons are captured by Al\(_2\)O\(_3\) NP, which reduces the movement of negative ions and causes only negative charges to be...
left in the region. As a result, superposition spatial electric fields are present, which reduces distortion of the external applied electric field. The Al\textsubscript{2}O\textsubscript{3} produced a potential well that is required for trapping electrons. Hence, when negative

![Graph showing range of positive and negative lightning impulse breakdown voltage enhancement of palm oil compared to mineral oil studied by various scholars from 2014-2021.](image)

**FIGURE 9.** Range of positive and negative lightning impulse breakdown voltage enhancement of palm oil compared to mineral oil that has been studied by various scholars from 2014-2021. Structure of legend: year published-reference number-types of palm oil-testing method-types of electrode-gap distance between electrodes; rising method: RIS, up-and-down method: UPDOWN, multiple level method: MULTI, SS: sphere-sphere, NS: needle-sphere, NP: needle-plane, ∗: data read from the graph, X: no data available.

**TABLE 6.** The lightning impulse breakdown voltages information studied by different researchers.

| Year | Ref. No. | Types of Oil | Distance of electrode (mm)/LIBDV testing method | Types of electrodes | Negative LI (kV) | Positive LI (kV) | Standard |
|------|----------|--------------|-----------------------------------------------|--------------------|-----------------|------------------|----------|
| 2021 | [154]    | RBDPO        | 3.8                                           | Sphere-sphere      | 208.6           | -                | IEC 60897 |
| 2018 | [150]    | RBDPO        | 25 / rising                                   | Needle-plane       | 93              | 65               | IEC 60897 |
|      |          |              |                                               | Needle-sphere      | 128             | 111              |          |
| 2018 | [3]      | RBDPO olein  | 3.8 / rising                                  | Sphere-sphere      | 206             | 200              | IEC 60897 |
|      |          |              | 3.8 / up and down                             |                    | 205             | -                |          |
|      |          |              | 3.8 / multiple                                |                    | 210             | -                |          |
|      |          |              | 2.0 / rising                                  |                    | 130.67          | 126              |          |
|      |          |              | 2.0 / up and down                             |                    | 128.83          | -                |          |
|      |          |              | 2.0 / multiple                                |                    | 130             | -                |          |
| 2018 | [155]    | RBDPO        | 3.8                                           | Sphere-sphere      | 206             | -                | IEC 60897 |
| 2016*| [156]    | RBDPO        | 2.0 / rising                                  | Needle-sphere      | 46              | 45               | IEC 60897 |
|      |          |              | 2.0 / up and down                             |                    | 45              | -                |          |
|      |          |              | 2.0 / multiple                                |                    | 50              | -                |          |
|      |          |              | 3.8 / rising                                  |                    | 57              | 58               |          |
|      |          |              | 3.8 / up and down                             |                    | 55              | -                |          |
|      |          |              | 3.8 / multiple                                |                    | 60              | -                |          |
|      |          |              | 6.0 / rising                                  |                    | 64              | 67               |          |
|      |          |              | 6.0 / up and down                             |                    | 63              | -                |          |
|      |          |              | 6.0 / multiple                                |                    | 65              | -                |          |
| 2015 | [149]    | RBDPO        | 3.8 / rising                                  | Needle-sphere      | 58              | -                | IEC 60897 |
|      |          |              | 3.8 / rising                                  |                    | 67              | -                |          |
|      |          |              | 3.8 / up-and-down                             |                    | 54.6            | -                |          |
|      |          |              | 6.0 / up-and-down                             |                    | 62.9            | -                |          |
| 2014 | [157]    | RBDPO Olein  | 2.0 / rising                                  | Sphere-sphere      | -               | 109.7            | IEC 60897 |
|      |          |              | 2.0 / up and down                             |                    | -               | 99               |          |
| 2014 | [153]    | RBDPO        | 25 / rising                                   | Needle-sphere      | 130             | 118              | IEC 60897 |
LIBDV is applied, positive and negative ions accumulate at the tip of needle electrodes weakening the nearby electric field [162], [163], [164]. In addition, the presence of CTAB surfactant provides an improvement of as much as 21.1% for positive polarity and 17% for negative polarity. It is believed that the stable RBDPO NF contributes to the LIBDV performance. A stable nanofluid is obtained once the electrical double layer repulsive force surpasses the Van der Waals attractive force, which prevents the clustering of the NP [4], [49]. The electrostatic and hydrophobic interactions between CTAB molecules and the Al$_2$O$_3$ surface contribute to the stability of NF. Compared to other surfactants, CTAB is more prominent in the adsorption of the Al$_2$O$_3$ surface, which stabilises the overall charge neutrality and thus forms an electrical double layer to create mutual repulsion and prevent aggregation.

To comprehend why RBDPO-NF has different LIBDV attributes than pure RBDPO, one must first comprehend how the presence of the NP in the oil alters the basic electrodynamic processes. The NP's charge relaxation time constant has a big impact on how much the electrodynamic processes in the oil are modified. If the charge relaxation time constant of the NP is short in comparison to the time for streamer growth, the presence of the NP in the RBDPO-NF will radically affect the electrodynamics. Furthermore, according to Hwang et al. [145], another reason behind the improvement of LIBDV is the electron attachment onto NP that leads to a significant reduction of fast-moving electrons and the formation of negatively charged nanoparticles with low mobility. This process reduces the electrical conductivity and increases the potential drop along the streamer channel in NF.

IV. PHYSICAL PROPERTIES OF PALM OIL AND NANOFLUID

A. VISCOSITY

Viscosity is a measure of the oil's resistance to continuous flow in the absence of external forces. The kinematic viscosity of insulating oil is its warmth-switching capacity, which indicates its cooling properties. The kinematic viscosity must be within 3–16 mm$^2$s$^{-1}$ at 40°C for MO and 16–37 mm$^2$s$^{-1}$ for VO, according to the ISO 3104 and ASTM D445 standards [165]. According to ASTM D6871 [39], the value of kinematic viscosity should be lower than 50 mm$^2$s$^{-1}$ at 40°C and 15 mm$^2$s$^{-1}$ at 100°C. Equation (4) shows the calculation of kinematic viscosity.

$$ v = Ct $$

where

- $v$: kinematic viscosity (mm$^2$s$^{-1}$)
- $C$: calibration constant of the viscometer (mm$^2$ s$^{-2}$)
- $t$: flow time (s)

A quality oil should have a low viscosity so that it resists the normal flow of oil and does not interfere with the cooling of a transformer. The viscosity should rise when the temperature drops and vice versa. Greater viscosity would result in higher hot-spot temperatures within the transformer. Fig. 10 shows the comparison of viscosity for various types of PO based on previous studies from 2003-2022. The graph shows that the viscosity of PO studied by Bakrutheen et al. [94] exceeds the recommended value at 40°C by more than 160%. However, when compared to the MO, PO gains a 22.29% enhancement on ACBDV results. It contradicts the theory, which could be due to the low-fat content of the PO examined by the author. In terms of kinematic viscosity at 100°C, all of the oil samples tested by the researchers were below the ASTM recommendation value.

In the year 2021, Mohd et al. [73] measured the kinematic viscosity of different types of PO at 40°C and 100°C. In comparison to the acceptable limit specified in ASTM D6871, all the studied PO have lower values ranging from 16.68 mm$^2$s$^{-1}$ (RBDPO with methyl laurate) to 40.49 mm$^2$s$^{-1}$ (RBDPO) at 40°C and from 4.84 mm$^2$s$^{-1}$ (RBDPO with caprylic acid) to 8.34 mm$^2$s$^{-1}$ (RBDPO) at 100°C. It is also demonstrated that RBDPO has a higher kinematic viscosity than RBDPKO with a difference of 25.29%. This is because RBDPO contains a higher composition of long-chain fatty acids, which account for more than 80% of the total fatty acid composition. According to Hoekman et al. [166], the kinematic viscosity of insulating oil is highly dependent on the composition structure and molecular size. Another study by Yaacob and Alsaedi [82] investigated the kinematic viscosity of samples of refined palm oil (RPO), CPO, and their derivatives (CP8 and CP10) with reduced fatty acid content. It is found that the viscosity of CP8 and CP10 derivatives is found to be reduced by 88.43% at 40°C and 83.96% at 100°C compared to CPO, which is in agreement with findings in [77] and [83]. These findings imply that lowering the fat content of PO causes low viscosity properties, hence allowing a more efficient dissipation of heat transfer ability [162].

Hussin et al. [133] observed the kinematic viscosity of conductive NP (ZnO) and non-conductive NP (ZrO$_2$) dispersed with PO. Adding NP has successfully reduced the viscosity of PO by 13-33%. PO-ZrO$_2$ at 0.0015 g/L concentration obtains the lowest viscosity, which is 35.89 mm$^2$s$^{-1}$ compared to pure PO (53.64 mm$^2$s$^{-1}$). For PO-ZnO, the lowest viscosity is 44.33 mm$^2$s$^{-1}$ at 0.0015 g/L concentration. It has been suggested that the ultrasound waves generated by the sonication method provide energy to the oil molecules, allowing them to vibrate more rapidly. This vibration generates a strong shear and stretching force within the molecule, enabling the molecules to move away from the initial position. As a consequence, both the cavitation and viscosity are reduced. This phenomenon is determined by the amplitude, processing time, and temperature of the oil when subjected to sonication radiation. Other parameters, such as the type and concentration/ weight of NP added to the PO, should be considered as a possible cause of viscosity reduction [168], [169].
The fire point should be greater than 300°C indoors or outdoors [174]. The elevated flash admissible value that is at the temperature range from 140°C for good insulation, power transformer oil must achieve the points in accordance with the ASTM D92 method. However, set by ASTM D6871 [39] for VO is 275°C presence of the flame. The flash point minimum requirement point, is defined as the temperature at which the oil surface escaping, the flash point is normally a few degrees lower than in an open cup. The flash point is the temperature at which oil releases sufficient vapour to form a flammable combination with air, resulting in an ignitable mixture and a brief flash. A higher flash point suggests that the oil is less flammable [172]. The fire point, also known as the flame point, is defined as the temperature at which the oil surface releases enough vapour to sustain a fire for 5 seconds in the presence of the flame. The flash point minimum requirement set by ASTM D6871 [39] for VO is 275°C, and 300°C for fire points in accordance with the ASTM D92 method. However, for good insulation, power transformer oil must achieve the admissible value that is at the temperature range from 140°C to 300°C [168]. According to the National Electrical Code, the fire point should be greater than 300°C when installing a transformer indoors or outdoors [174]. The elevated flash point and fire point are essential for ensuring higher safety standards during the in-service operation of transformers.

Fig. 11 shows the previous studies on the flash points and fire points of PO by various researchers from 2004-2022. All of the flash points result of PO was in the range of acceptable limit for application in transformer [175], [176], [177], [178], [179]. However, only a few studies have found that the results of fire points exceed the limit. Senthilkum et al. [180] and Aditama [83] studied the flash point of RBDPO and obtained high flash point values of 320°C and 424°C. Mohd et al. [73] compared the flash point and fire points of several types of RBDPO with and without additives. It was discovered that RBDPO without any additives has a significant flash point and fire points that also exceed 300°C temperature. Similar results are obtained when caprylic acid is combined with RBDPO. In 2021, Walvekar et al. [181] investigated the flash point of palm oil methyl ester (POME), which resulted in a temperature of 175.5°C compared to the MO at 146.5°C. In general, POME has a high saturated fatty acid composition of 17 carbons, which results in a greater flash point [182], [183]. A high flash point is also associated with a high content of methyl oleate, which is present in POME. It is shown that most of the types of PO can be classified as less flammable dielectric coolants. Additionally, PO does not lead to an exterior fire, and the combustion products are non-toxic. Therefore, PO is particularly applicable for installation in high-risk industrial areas such as steel mills, oil and gas offshore facilities, wind power farms, and so on.

VI. TAN δ AND RELATIVE PERMITTIVITY
Condition monitoring of transformers helps determine the maintenance and replacement decisions of transformers. In general, tan δ, resistivity, and relative permittivity (RP) are important parameters that define the condition of oil in the transformer. These three parameters are tested according to IEC 60247 [184] standards and ASTM D924 [185] standards. Tan δ or known as the dielectric dissipation factor, loss angle, or power factor, provides information on the quality of the transformer oil. It is desirable to have low tan δ as possible because high tan δ indicates the presence of contamination, deterioration, or existence of moisture, carbon, varnish or etc. The dielectric constant, or relative permittivity, of transformer oil is an important parameter in determining how the electric field behaves in the oil and is generally related to the polarizability nature of insulation.

Fig. 12 depicts the range of tan δ for PO by researchers from 2003-2022. Based on IEC 60247 [184], the permissible limit of tan δ is 0.1 (maximum), while the IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers [186] suggests that 0.005 is the maximum value for VO. However, prompt investigation is recommended for tan δ to exceed 0.03 at normal temperature. Although different acceptable values are recommended, the differences are quite small. Compared to the IEC 60247, all researchers agreed that PO has a low tan δ value,
especially for PKO (0.00129) and RBDPO category 8 (CP8) (0.0016). However, referring to the IEEE recommendation, only some of the studies obtain less than the recommendation value [77], [82], [90], [92], [102], [109]. Hamid et al. [87] tested the tan δ of PKO-NF by adding Al₂O₃ and TiO₂ NP. It is reported that both NP contribute to the decrement of RP value. However, Nor et al. [113] obtained different results, where TiO₂ enhanced the tan δ value by 12.9% compared to pure RBDPO.

Ideal insulation is loss-free and represents a pure capacitor. However, when a voltage is applied to the insulation, some kinds of active losses occur; conduction losses, polarisation losses, and ionisation losses. As losses exist in the insulator, the resistive current contribution to the measurement increases and causes the loss angle to subsequently increase. Hence, the tan δ is no longer at 0% which signifies deterioration or contamination. There is a clear relationship between tan δ and the resistivity of insulating oil. If the tan δ value is increased, the resistivity value will be decreased and vice versa. In general, both tan δ and resistivity are not required to be tested for the same piece of insulator.

Fig. 13 depicts the RP of PO studied by different researchers. The RP of transformer oil is approximately between 2.1-2.4 in frequency ranges from 1 Hz – 100 Hz [185]. When the cellulose insulation is impregnated with transformer oil, the RP will approach 7 [187]. Based on Fig. 13, most of the studies found that the RP of PO is more than 2.4. While referring to the ASTM D924, the RP is in the range between 3.1-3.2 for VO samples. Sari et al. [92], Amin et al. [97] and Rajab et al. [107] obtain the RP within that range. It seems that PO makes the effective RP as transformer oil and beyond the guidelines value. However, different material consists of different RP value. High RP allows the insulator to withstand the electrical stresses of the transformer during operation. According to Sawada,
RP is contributed by electronic, atomic and dipole polarisation [188]. Furthermore, the presence of triglycerides in PO naturally causes orientation polarisation, whereas transformer oil is primarily composed of refined petroleum, which contains non-polar alkane molecules.

**FIGURE 13.** Comparison of relative permittivity for various types of PO based on previous studies from 2003-2022. Structure of legend: year published-reference number-types of PO-types of nanoparticles: ∗: data read from the graph; X: no data available.

**VII. CONCLUSION**

Palm oil is one of Malaysia’s primary industries and more than half of palm oil (PO) is planted in the area of Peninsular Malaysia. PO has been seen as a potential substitute for petroleum-based mineral oil (MO) because it is environmentally friendly, biodegradable, and renewable. Hence, this review article updates the reader on the latest developments of palm oil (PO) and palm oil-based nanofluids (PO-NF) as green transformer oils. Multiple experimental works carried out by different researchers are conducted on PO and PO-NF from 2003-2022. Based on the findings, it is clear that PO meets international standards and that the majority of its electrical, physical, and dielectric properties are comparable to MO. It has also been determined that the most consistent and promising type of PO is refined, bleached, and deodorised palm oil (RBDPO), which contains a balanced saturated and unsaturated fatty acid composition. Furthermore, when CuO nanoparticles are added to RBDPO with the aid of CTAB surfactant, a 173.42% increment in AC breakdown voltage is obtained compared to the RBDPO without nanoparticles. For the lightning impulse breakdown voltage characteristics, regardless of polarity or test methods, the RBDPO results get lower than MO. However, when adding nanoparticles, the RBDPO slightly increased due to the modification of the electrodynamic process caused by nanoparticles. There is also a lack of studies conducted by researchers on the lightning impulse breakdown voltage for different types of PO and nanoparticles. Due to the possibility of direct lightning current injection and overvoltage occurring in transformers in real life, it is critical to examine the lightning impulse breakdown voltage. When it comes to viscosity, most studies yield a lower value than the standard recommendation. Low viscosity is necessary to reduce the hot-spot temperature in a transformer. The flash point and fire point of various types of PO are within the acceptable limit. The researchers also agreed that PO has a low tan δ value, especially palm kernel oil (PKO) and RBDPO. For relative permittivity, the recommended value of transformer oil is within 2.10-2.40, while for natural ester oil, the rate is between 3.1-3.2, according to ASTM D924. The relative permittivity of RBDPO is within the range of 2.09–3.25. In addition to all of these studies, it is essential to review the partial discharge breakdown voltage, thermal behaviour, and dissolved gas analysis of PO and PO-NF in the future. Hence, it can be concluded that the studies on PO require further attention from the scientific community, as the oil may have a significant contribution to the reduction of environmental impact by MO.

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