

TOPICAL REVIEW

A Review on Palm Oil-Based Nanofluids as a Future Resource for Green Transformer Insulation System

NUR S. SUHAIMI¹, MOHD T. ISHAK¹, (Member, IEEE), ABDUL R. A. RAHMAN¹,
MUHAMMAD F. MD. DIN¹, MOHD Z. Z. ABIDIN², AND AZHAR K. KHAIRI²

¹Faculty of Engineering, National Defence University of Malaysia, Sungai Besi Camp, Kuala Lumpur 57000, Malaysia

²SGB MY Sdn Bhd, Nilai, Negeri Sembilan Darul Khusus 71800, Malaysia

Corresponding author: Mohd T. Ishak (mtaufiq@upnm.edu.my)

This work was supported in part by Grant FRGS/1/2018/TK04/UPNM/02/03.

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).

The associate editor coordinating the review of this manuscript and approving it for publication was Roberto Sacile¹.

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_4H_{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].

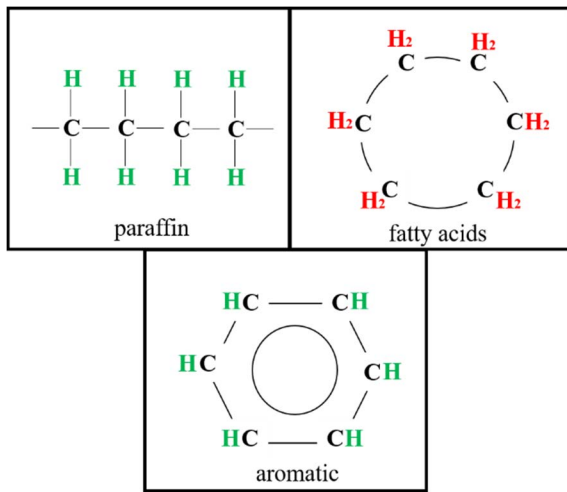


FIGURE 1. Hydrocarbon compounds in mineral oil.

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.

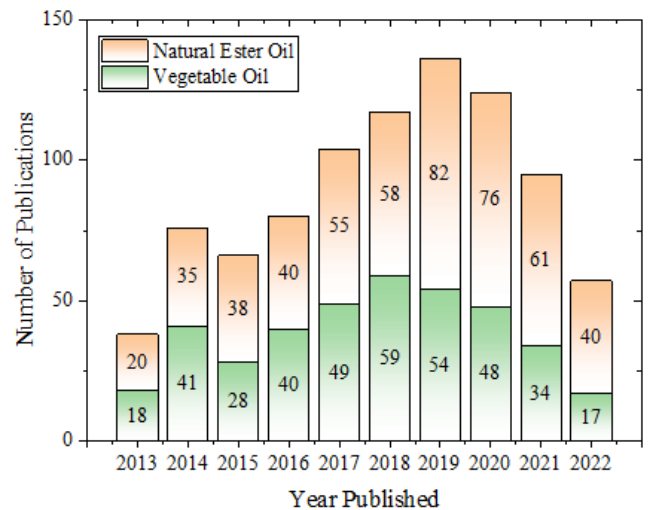


FIGURE 2. Year-wise publication on keyword using 'vegetable oil' and 'natural ester oil' for transformer application based on IEEE Xplore database.

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]. RBDPO 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 RBDPO 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].

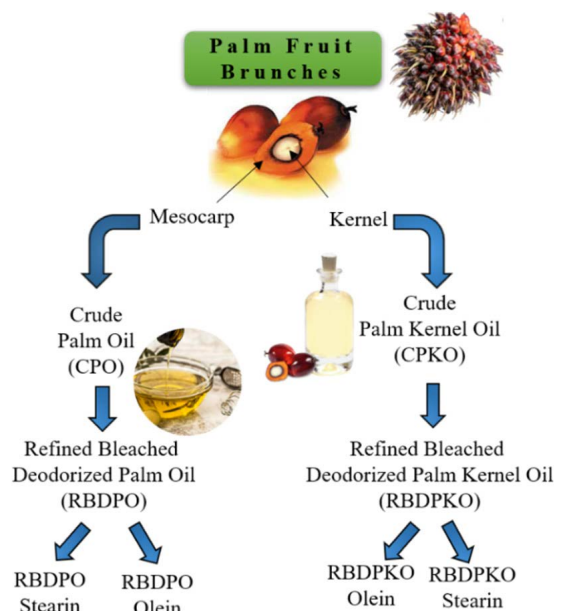


FIGURE 3. Processing of palm oil, palm kernel oil and fractionation process.

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_a , R_b , 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].

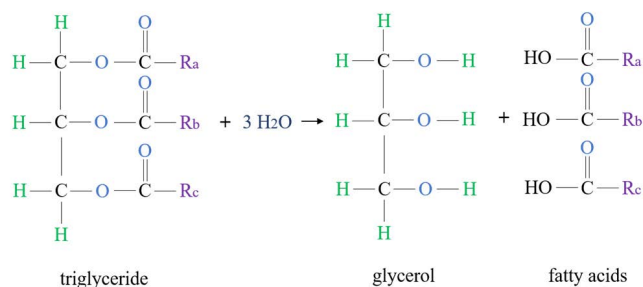


FIGURE 4. General chemical composition of palm oil.

III. ELECTRICAL PROPERTIES OF PALM OIL AND NANOFUID




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			
Electrode material	Polished Brass	Brass	Brass/ Bronze/ Stainless Steel
Size of electrodes	Diameter: 36 mm	Diameter: 25.4 mm Thickness: ≥ 3.18 mm Sharp edges radius: ≤ 0.254 mm	Diameter: 12.5 mm – 13 mm
Electrode gap	2 mm/ 1 mm	2.54 mm	2.5 mm
Voltage rate of rising	0.5 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. Cloud 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

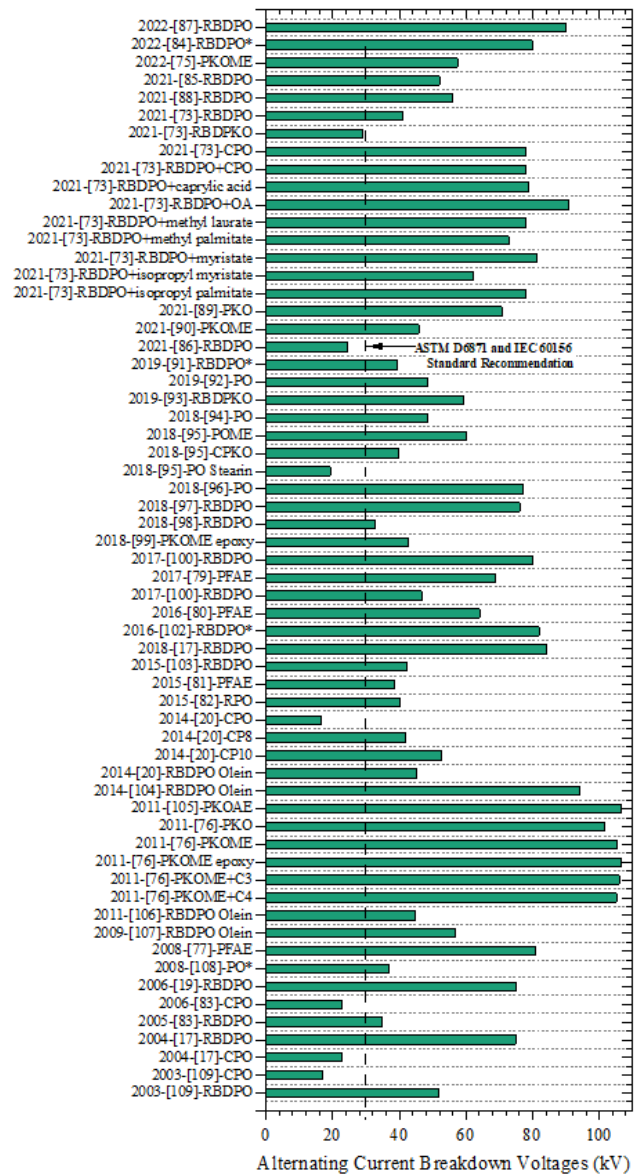


FIGURE 5. Range of AC breakdown voltage results of palm oil compared to mineral oil has been studied by various scholars from 2003-2022. Structure of the legend: year published-reference number-types of palm oil; * data read from the graph.

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]	RBDPO	89.89	IEC 60156
2022*	[84]	RBDPO	80	IEC 60156
2022	[75]	PKOME	57.5	ASTM D1816
2021	[85]	RBDPO	52.09	IEC 60156
2021	[88]	RBDPO	56.15	IEC 60156
2021	[73]	RBDPO	40.90	ASTM D1816
		RBDPKO	29.1	D1816
		CPO	78.1	
		RBDPO + CPO	78.0	
		RBDPO + caprylic acid	78.9	
		RBDPO + oleic acid	90.8	
		RBDPO + methyl laurate	78.1	
		RBDPO + methyl palmitate	72.8	
		RBDPO + myristate	81.2	
		RBDPO + isopropyl myristate	62.1	
		RBDPO + isopropyl palmitate	78.1	
2021	[89]	PKO	70.7	IEC 60156
2021	[90]	PKOME	45.91	ASTM D1816
2021	[86]	RBDPO	24.6	IEC 60156
2019*	[91]	RBDPO	39.5	IEC 60156
2019	[92]	PO	48.50	IEC 60156
2019	[93]	RBDPKO	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]	RBDPO	76.17	IEC 60156
2018	[98]	RBDPO	32.65	IEC 60156
2018	[99]	PKOME epoxy	42.58	ASTM D1816
2017	[100]	RBDPO	80.062	IEC 60156
2017	[79]	PFAE	68.75	ASTM D1816
2017	[101]	RBDPO	46.72	IEC 60156
2016	[80]	PFAE	64.10	ASTM D1816
2016*	[102]	RBDPO	82	IEC 60156
2015	[17]	RBDPO	84.23	IEC 60156
2015	[103]	RBDPO	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
		CP8	41.92	ASTM D1816
		CP10	52.73	
		RBDPO Olein	45.25	
2014	[104]	RBDPO 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	IEC 60156
		PKOME + C3	106	
		PKOME + C4	105.25	
2011	[106]	RBDPO Olein	45	
2009	[107]	RBDPO Olein	57	
2008	[77]	PFAE	81	IEC 60156
2008*	[108]	PO	37	IEC 156/ ASTM D877

TABLE 2. (Continued.) The AC breakdown voltages of various types of palm oil studied by different researchers.

2006	[19]	RBDPO	75	ASTM D1816
2005	[83]	CPO	23	ASTM D1816
		RBDPO	35	IEC 296
2004	[17]	RBDPO	75	ASTM D1816/ IEC 296
		CPO	23	
2003	[109]	CPO	17	IEC 296
		RBDPO	52	

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 Cetrimum 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 Fe₃O₄-RBDPO, Al₂O₃-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 Al₂O₃-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 absorbed on the surface of Al₂O₃ 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 Suksri [88] investigated the ACBDV of RBDPO and POME with nano-graphene 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 (TiO₂) or known as Titania, is considered to be one of the three most-produced NPs, along with SiO₂ and ZnO [120]. It is a naturally occurring mineral existing in several crystalline forms (rutile and anatase). TiO₂ 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 TiO₂, while some of them studied the ACBDV effect of TiO₂ on PKO, POME, and PFAE. However, it is interesting that all of the studies gained quite an enhancement on ACBDV. In 2021, Muangpratoom [121] found that after adding TiO₂, 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 TiO₂ and a 13.70% increment after dispersing TiO₂ 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 TiO₂ in this case. In addition, Makmud *et al.* [122] studied TiO₂ 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 TiO₂ 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 Suksri [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.

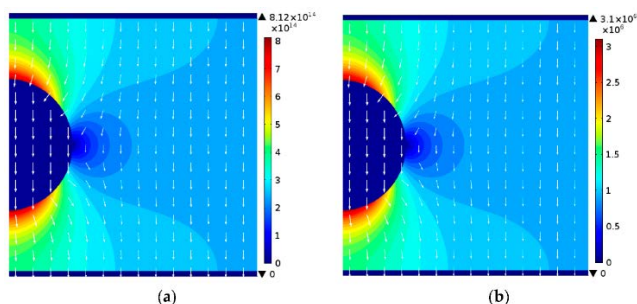


FIGURE 6. The electric displacement field and current density distributions of (a) Fe₂O₃ and (b) TiO₂ using Finite Element Analysis (FEA) [118].

d: IRON OXIDE

Iron (II, III) Oxide is written as FeO/ Fe₃O₄ (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. Fe₃O₄ 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 Fe₃O₄, where Mohamad *et al.* [79], [80] reported 45.16% and 41.61% enhancement of ACBDV at 0.01 g/L weight concentration of Fe₃O₄ with the aid of OA compared to pure PFAE. The improvement is considered to be due to the electron scavenger action of Fe₃O₄ 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-Fe₃O₄, and RBDPO-Fe₃O₄ synthesis with CTAB. In brief, the introduction of Fe₃O₄ reduced the ACBDV performance by about 8.86% (without CTAB) and 3.8% (with CTAB). Previous research has shown that adding Fe₃O₄ to other types of VO improves ACBDV significantly, which contradicts RBDPO-Fe₃O₄. Because of the complex composition of RBDPO, Fe₃O₄ 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 Fe₃O₄'s having higher electrical conductivity, which is 10⁶ times higher than Fe₂O₃. Besides, a study also reported that Fe₃O₄ 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 Suksri [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 (1×10^2 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 (BaTiO_3) is considered one of the candidates for a high dielectric insulator. The dielectric constant of BaTiO_3 is 100 times higher than that of SiO_2 NP [137]. Muangpratoom [121] conducted an experiment on RBDPO that contains BaTiO_3 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- BaTiO_3 NF. This means that BaTiO_3 NP is able to trap electrons in the oil sample due to the polarisation effect caused by NP. Besides, RBDPO- BaTiO_3 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 (SiO_2), also known as Silica. SiO_2 is a compound of Silicon and Oxygen that is linked by the covalent bond. Many studies showed promising results after adding SiO_2 to MO [138], [139] and VO [140]. As a result, Yahya and Amirrazli [98] were motivated to test the influence of SiO_2 on RBDPO by referring to the IEC 60156 standard. In contrast, the ACBDV of RBDPO- SiO_2 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 SiO_2 and RBDPO.

k: ZIRCONIUM DIOXIDE

Zirconium Dioxide (ZrO_2) is available in many forms; nanodots, nanofluids, and nanocrystals. ZrO_2 consists of high chemical stability, excellent corrosion-resisting materials, and is an important dielectric material [141]. In one article, it is reported that ZrO_2 NP can be an effective agent for enhanced oil recovery [142]. The ACBDV of transformer oil with ZrO_2 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 ZrO_2 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-ZrO₂ 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 ZrO₂ 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 (τ_r), which is defined as the time required for the NP to capture (trap) and loosen up (release) the charge. The relaxation time (τ_r) is denoted by (1) [145]:

$$\tau_r = \frac{2\varepsilon_1 + \varepsilon_2}{2\sigma_1 + \sigma_2} \quad (1)$$

where σ_1 and σ_2 are electrical conductivities of base fluid and nanoparticles, respectively, and ε_1 and ε_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 ZrO₂ 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 μ 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

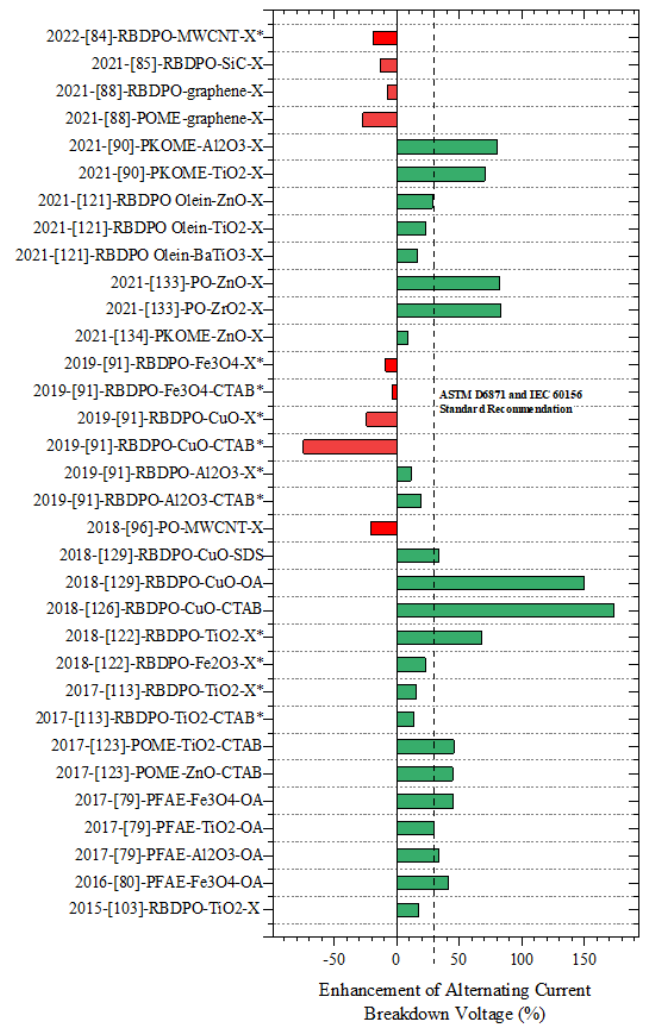


FIGURE 7. Range of AC breakdown voltage enhancement of palm oil-based nanofluid compared to their based oil studied by various scholars from 2015-2022. Structure of legend: year published-reference number-types of palm oil-types of nanoparticles-surfactant; *: data read from the graph, X: no data available.

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

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
		POME	Graphene		43.65	60156
2021	[90]	PKOME	Al ₂ O ₃		64.07	ASTM D1816
			TiO ₂		60.60	D1816
2021	[121]	RBDPO	ZnO		54.7	IEC 60156
		Olein	TiO ₂		52.4	
			BaTiO ₃		49.3	
2021	[133]	PO	ZnO		69.28	
			ZrO ₂		69.57	
2021	[134]	PKOME	ZnO		132.45	ASTM D1816
2019*	[91]	RBDPO	Fe ₃ O ₄		36	IEC 60156
			Fe ₃ O ₄	CTAB	38	
			CuO	CTAB	30	
			CuO	CTAB	10	
			Al ₂ O ₃		44	
			Al ₂ O ₃	CTAB	47	
2018	[96]	PO	MWCNT		61	IEC 60156
2018	[129]	RBDPO	CuO	SDS	52.75	ASTM D1816
			CuO	OA	98.5	
			CuO	CTAB	108	
2018*	[122]	RBDPO	TiO ₂		130	ASTM D1816
			Fe ₂ O ₃		95	D1816
2017*	[113]	RBDPO	TiO ₂		46.8	ASTM D1816
			TiO ₂	CTAB	46.05	D1816
2017	[123]	POME	TiO ₂	CTAB	36.37	ASTM D1816
			ZnO	CTAB	34.12	
2017	[79]	PFAE	Fe ₃ O ₄	OA	99.8	ASTM D1816
			TiO ₂	OA	89.17	D1816
			Al ₂ O ₃	OA	92.17	
2016	[80]	PFAE	Fe ₃ O ₄	OA	90.77	ASTM D1816
2015	[103]	RBDPO	TiO ₂		50	ASTM D1816

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

Standards	ASTM D3300	IEC 60897
Shape of electrodes		
Electrode material	Steel/ Brass	Steel
Electrode gap	25.4 mm for point-sphere 3.8 mm for sphere-sphere	10-25 mm
Voltage increasing method	Step by step: 3 shots per step	Step by step: 1 shot per step
Time between breakdowns	Minimum 30s	Minimum 60s

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.

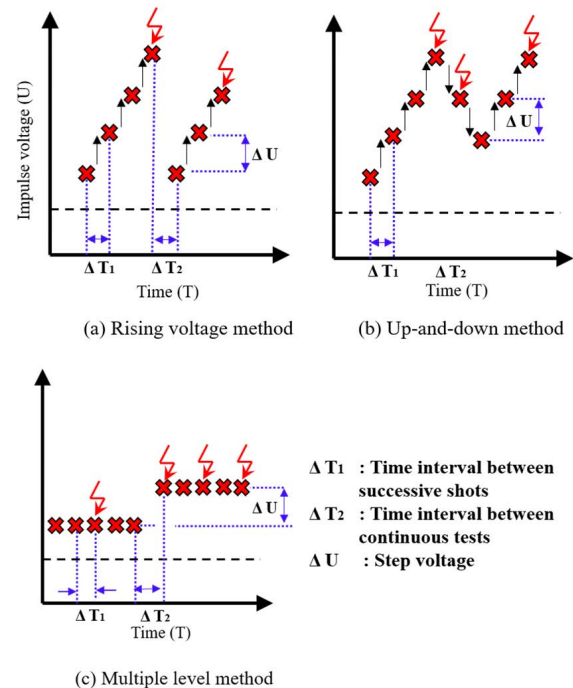


FIGURE 8. Sketch of methodology for lightning impulse test.

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].

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 between each breakdown (s)	60	60	60
Total breakdown measurement	15	30	20

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].

$$n_0 = \sqrt{\frac{N_0 v_0}{\xi}} e^{-\frac{(u_0 - \Delta u_0)}{2kT}} \quad (2)$$

$$\Delta n_0 = \sqrt{\frac{q^3 E}{\pi \epsilon_0 \epsilon_r}} \quad (3)$$

where

n_0 : ion concentration

N_0 : number of ions

v_0 : relative thermal vibrational frequency between atomic clusters

ξ : 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

ϵ_0 : permittivity of vacuum

ϵ_r : relative permittivity

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

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 SiO₂ NP at a concentration of 0.5% improved MO LIBDV by 25%. Hessin *et al.* [160] discovered that adding Mn_{0.2}Ni_{0.8}Fe₂O₄ to MO increased LIBDV by 40%. Furthermore, Potivejkul *et al.* [161] investigated the effect of negative LIBDV of VO after adding TiO₂ 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 TiO₂ 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-TiO₂ 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-TiO₂ 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-TiO₂ 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-Al₂O₃ 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-Al₂O₃ shows significant performance under both positive and negative polarity. When the positive LIBDV is applied, high mobility electrons are captured by Al₂O₃ NP, which reduces the movement of negative ions and causes only negative charges to be

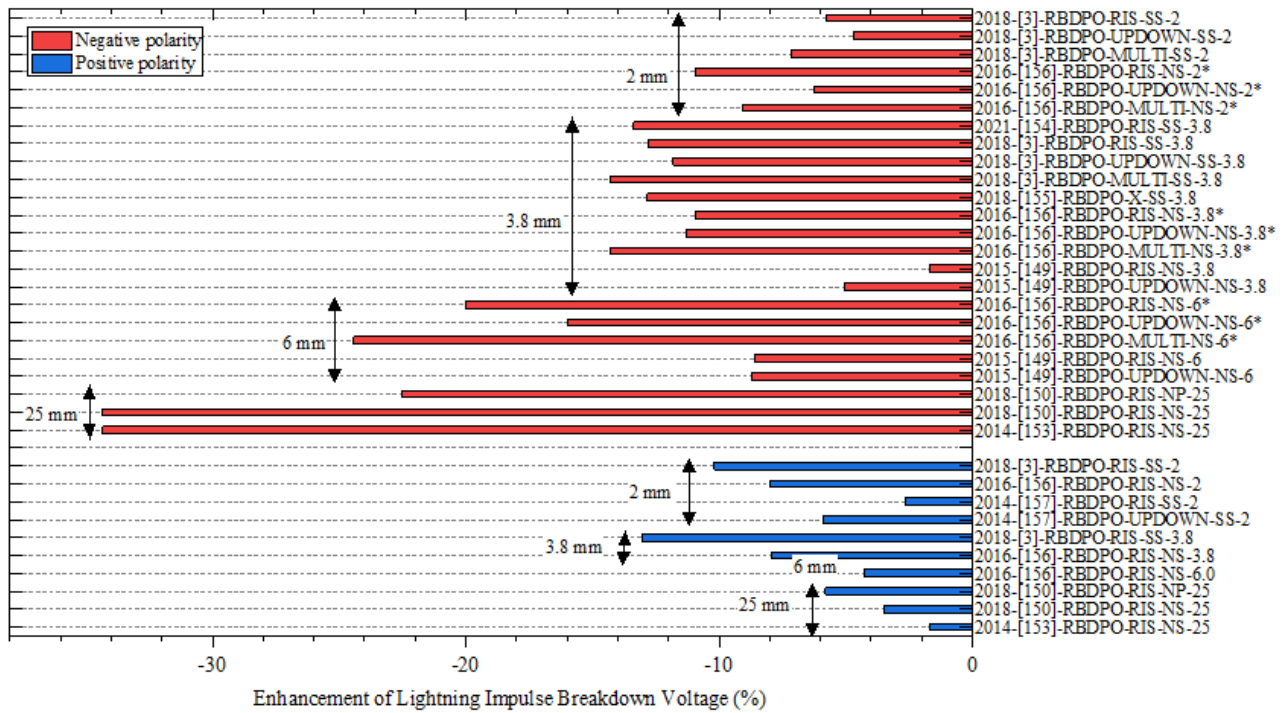


FIGURE 9. Range of positive and negative lightning impulse breakdown voltage enhancement of palm oil compared to mineral oil that has been studied by various scholars from 2014-2021. Structure of legend: year-published-reference number-types of palm oil-testing method-types of electrode-gap distance 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
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	-	
2015	[149]	RBDPO	6.0 / multiple		65	-	IEC 60897
			3.8 / rising	Needle-sphere	58	-	
			6.0 / rising		67	-	
			3.8 / up-and-down		54.6	-	
2014	[157]	RBDPO Olein	6.0 / up-and-down		62.9	-	IEC 60897
			2.0 / rising	Sphere-sphere	-	109.7	
2014	[153]	RBDPO	2.0 / up and down		-	99	IEC 60897
			25 / rising	Needle-sphere	130	118	

left in the region. As a result, superposition spatial electric fields are present, which reduces distortion of the external

applied electric field. The Al₂O₃ produced a potential well that is required for trapping electrons. Hence, when negative

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_2O_3 surface contribute to the stability of NF. Compared to other surfactants, CTAB is more prominent in the adsorption of the Al_2O_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 electrodynamic processes. 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^2s^{-1} at 40°C for MO and 16–37 mm^2s^{-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^2s^{-1} at 40°C and 15 mm^2s^{-1} at 100°C. Equation (4) shows the calculation of kinematic viscosity.

$$v = Ct \quad (4)$$

where

v : kinematic viscosity (mm^2s^{-1})

C : calibration constant of the viscometer ($\text{mm}^2 \text{s}^{-2}$)

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 Bakruteen *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^2s^{-1} (RBDPO with methyl laurate) to 40.49 mm^2s^{-1} (RBDPO) at 40°C and from 4.84 mm^2s^{-1} (RBDPO with caprylic acid) to 8.34 mm^2s^{-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^2s^{-1} compared to pure PO (53.64 mm^2s^{-1}). For PO-ZnO, the lowest viscosity is 44.33 mm^2s^{-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].

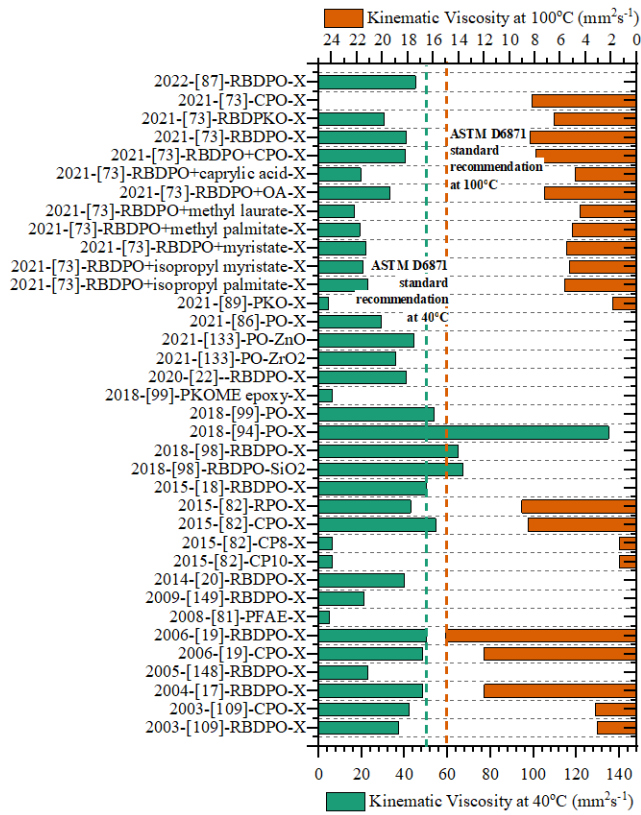


FIGURE 10. Comparison of flash point and fire point for various types of PO based on previous studies from 2006-2022. Structure of legend: year published-reference number-types of palm oil-types of nanoparticles-standard method: *:data read from the graph, X:no data available.

V. FLASH POINT AND FIRE POINT

The flammability of transformer oil is evaluated using flash point and fire point measurements. The flash point and fire point were tested in accordance with ASTM D92 [170] or ASTM D93 [171]. The main difference between those two methods is that ASTM D92 uses Cleveland open cup apparatus while ASTM D93 uses the Pensky-Marten closed-cup test. Because the closed-cup approach prevents vapours from 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,

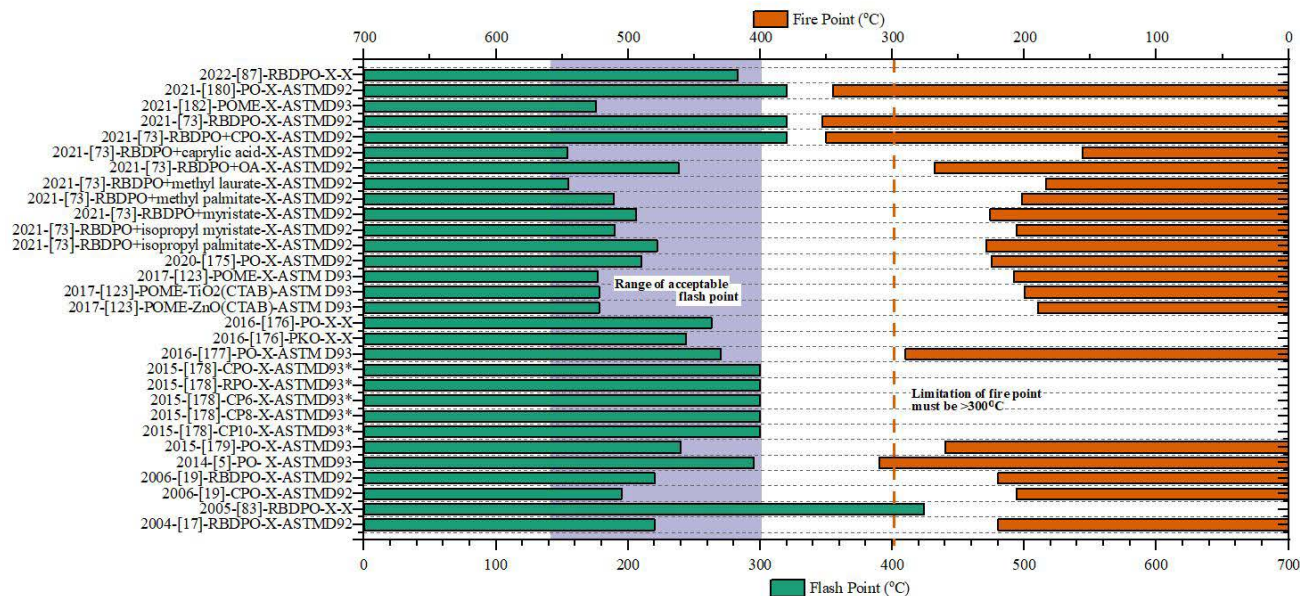


FIGURE 11. Comparison of flash point and fire point for various types of PO based on previous studies from 2006-2022. Structure of legend: year published-reference number-types of palm oil-types of nanoparticles-standard method: *:data read from the graph, X:no data available.

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 $\tan \delta$ of PKO-NF by adding Al_2O_3 and TiO_2 NP. It is reported that both NP contribute to the decrement of RP value. However, Nor *et al.* [113] obtained different results, where TiO_2 enhanced the $\tan \delta$ 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 $\tan \delta$ is no longer at 0 % which signifies deterioration or contamination. There is a clear relationship between $\tan \delta$ and the resistivity of insulating oil. If the $\tan \delta$ value is increased, the resistivity value will be decreased and vice versa. In general, both $\tan \delta$ 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,

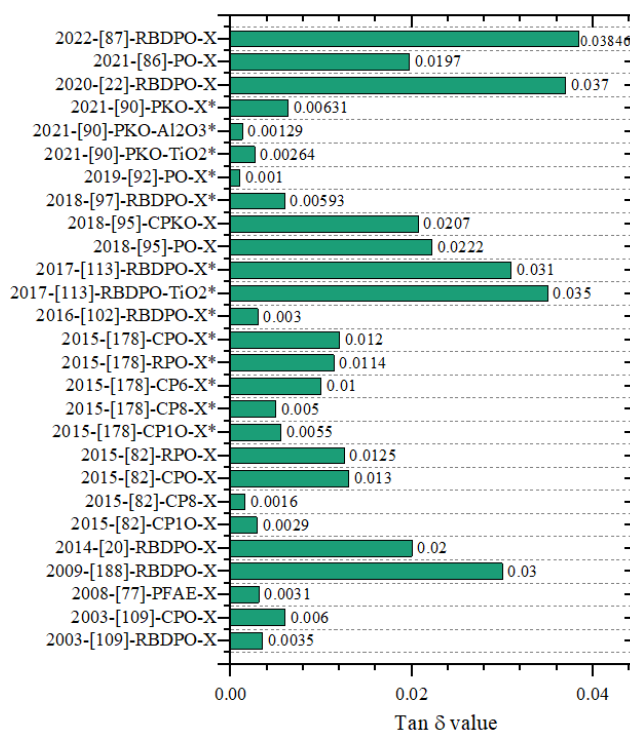


FIGURE 12. Comparison of $\tan \delta$ for various types of PO based on previous studies from 2003-2022. Structure of legend: year published-reference number-types of palm oil-types of nanoparticles: *: data read from the graph, X: no data available.

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, the

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.

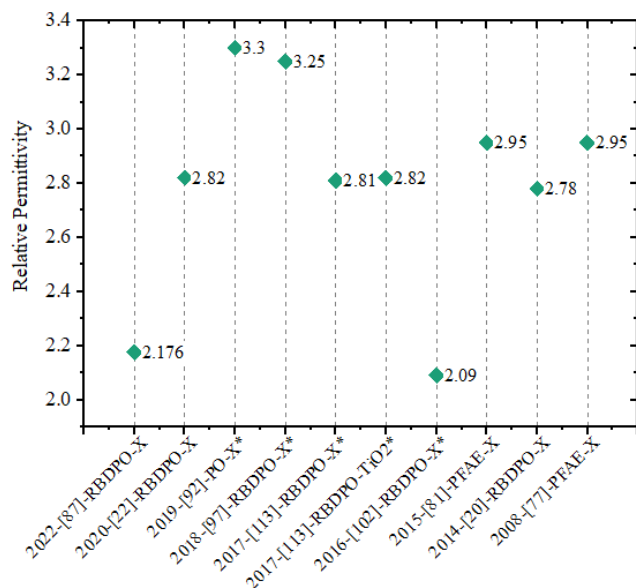


FIGURE 13. Comparison of relative permittivity for various types of PO based on previous studies from 2003-2022. Structure of legend: year published-reference number-types of palm oil-types of nanoparticles: *:data read from the graph, X: no data available.

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 $\tan \delta$ 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.

REFERENCES

- I. B. M. Taha, S. S. M. Ghoneim, and H. G. Zaini, "A fuzzy diagnostic system for incipient transformer faults based on DGA of the insulating transformer oils," *Int. Rev. Electr. Eng.*, vol. 11, no. 3, p. 305, Jun. 2016, doi: [10.15866/iree.v11i3.8453](https://doi.org/10.15866/iree.v11i3.8453).
- R. Phadungthin and J. Haema, "Proposed risk model of maintenance management for power transformer in transmission system," *Int. Rev. Electr. Eng.*, vol. 11, no. 1, p. 88, Feb. 2016, doi: [10.15866/iree.v11i1.7703](https://doi.org/10.15866/iree.v11i1.7703).
- N. Katim, M. Ishak, N. M. Amin, M. A. Hamid, K. A. Ahmad, and N. Azis, "Lightning breakdown voltage evaluation of palm oil and coconut oil as transformer oil under quasi-uniform field conditions," *Energies*, vol. 11, no. 10, p. 2676, Oct. 2018, doi: [10.3390/en11102676](https://doi.org/10.3390/en11102676).
- E. Yuliasuti, "Analysis of dielectric properties comparison between mineral oil and synthetic ester oil," M.S. thesis, Dept. Elect. Sustain. Energy, Fac. Elect. Eng., Math. Comput. Sci., Delft Univ. Technol., Jun. 2010.
- S. S. Kumar, M. W. Iruthayarajan, and M. Bakruteen, "Analysis of vegetable liquid insulating medium for applications in high voltage transformers," in *Proc. Int. Conf. Sci. Eng. Manag. Res. (ICSEMR)*, Nov. 2014, pp. 1-5, doi: [10.1109/ICSEMR.2014.7043606](https://doi.org/10.1109/ICSEMR.2014.7043606).
- R. Sanghi, "Chemistry behind the life of a transformer," *Resonance*, vol. 8, no. 6, pp. 17-23, Jun. 2003, doi: [10.1007/BF02837865](https://doi.org/10.1007/BF02837865).
- I. Hosier, A. Guushaa, E. Westenbrink, C. Rogers, A. Vaughan, and S. Swingler, "Aging of biodegradable oils and assessment of their suitability for high voltage applications," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 3, pp. 728-738, Jun. 2011, doi: [10.1109/TDEI.2011.5931059](https://doi.org/10.1109/TDEI.2011.5931059).
- M. Heathcote, *J&P Transformer Book*. Newnes, 2007, doi: [10.1016/B978-0-7506-8164-3.X5000-5](https://doi.org/10.1016/B978-0-7506-8164-3.X5000-5).
- Z. Wang, C. Yang, Z. Yang, C. E. Brown, B. P. Hollebhone, and S. A. Stout, "Petroleum biomarker fingerprinting for oil spill characterization and source identification," in *Standard Handbook Oil Spill Environmental Forensics*, 2nd ed. Amsterdam, The Netherlands: Elsevier, 2016, ch. 4, pp. 131-254, doi: [10.1016/B978-0-12-803832-1.00004-0](https://doi.org/10.1016/B978-0-12-803832-1.00004-0).
- E. O. Aluyor and M. Ori-jesu, "Biodegradation of mineral oils—A review," *Afr. J. Biotechnol.*, vol. 8, no. 6, pp. 1-6, 2009, doi: [10.4314/ajb.v8i6.59986](https://doi.org/10.4314/ajb.v8i6.59986).
- M. M. Jaffar, M. A. Nahil, and P. T. Williams, "Methane production from the pyrolysis-catalytic hydrogenation of waste biomass: Influence of process conditions and catalyst type," *Energy Fuels*, vol. 33, no. 8, pp. 7443-7457, Aug. 2019, doi: [10.1021/acs.energyfuels.9b01524](https://doi.org/10.1021/acs.energyfuels.9b01524).
- S. S. Lam, A. D. Russell, C. L. Lee, and H. A. Chase, "Microwave-heated pyrolysis of waste automotive engine oil: Influence of operation parameters on the yield, composition, and fuel properties of pyrolysis oil," *Fuel*, vol. 92, no. 1, pp. 327-339, Feb. 2012, doi: [10.1016/j.fuel.2011.07.027](https://doi.org/10.1016/j.fuel.2011.07.027).

- [13] K. R. Aglawe, R. K. Yadav, and S. B. Thool, "Preparation, applications and challenges of nanofluids in electronic cooling: A systematic review," *Mater. Today: Proc.*, vol. 43, pp. 366–372, Jan. 2021, doi: 10.1016/j.matpr.2020.11.679.
- [14] K. Rajan, A. M. Babu, R. Paladi, S. Nallusamy, and K. R. S. Kumar, "Performance assessment of DI diesel engine using waste transformer oil with different compression ratios," *Int. J. Ambient Energy*, vol. 43, no. 1, pp. 3536–3544, Dec. 2022, doi: 10.1080/01430750.2020.1839548.
- [15] P. Boss and T. V. Oommen, "New insulating fluids for transformers based on biodegradable high oleic vegetable oil and ester fluid," in *Proc. IEE Colloq. Insulating Liquids*, vol. 119, 1999, p. 7, doi: 10.1049/ic:19990669.
- [16] J. Tokunaga, M. Nikaido, H. Koide, and T. Hikosaka, "Palm fatty acid ester as biodegradable dielectric fluid in transformers: A review," *IEEE Elect. Insul. Mag.*, vol. 35, no. 2, pp. 34–46, Mar. 2019, doi: 10.1109/MEI.2019.8636104.
- [17] U. U. Abdullahi, S. M. Bashi, R. Yurius, and H. J. A. Nurdin, "The potentials of palm oil as a dielectric fluid," in *Proc. Nat. Power Energy Conf. (PECon)*, Nov. 2004, pp. 224–228, doi: 10.1109/PECON.2004.1461648.
- [18] K. Azmi, A. Ahmad, and M. Kamarol, "Study of dielectric properties of a potential RBD palm oil and RBD soybean oil mixture as insulating liquid in transformer," *J. Electr. Eng. Technol.*, vol. 10, no. 5, pp. 2105–2119, Sep. 2015, doi: 10.5370/JEET.2015.10.5.2105.
- [19] S. M. Bashi, U. U. Abdullahi, R. Yunus, and A. Nordin, "Use of natural vegetable oils as alternative dielectric transformer coolants," *J.-Inst. Eng.*, vol. 67, no. 2, pp. 4–9, 2006.
- [20] N. A. Mohamad, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, M. T. Ishak, and Z. Yaakub, "A study on the dielectric properties of palm oil and coconut oil," in *Proc. IEEE Int. Conf. Power Energy (PECon)*, Dec. 2014, pp. 109–112, doi: 10.1109/PECON.2014.7062423.
- [21] N. A. Mohamad, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, M. T. Ishak, and Z. Yaakub, "Investigation on the dielectric, physical and chemical properties of palm oil and coconut oil under open thermal ageing condition," *J. Electr. Eng. Technol.*, vol. 11, no. 3, pp. 690–698, May 2016, doi: 10.5370/JEET.2016.11.3.690.
- [22] N. A. Mohamad, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, and Z. Yaakub, "Effect of surfactants on the lightning breakdown voltage of palm oil and coconut oil based Al₂O₃ nanofluids," *Nanotechnology*, vol. 31, no. 42, Oct. 2020, Art. no. 425708, doi: 10.1088/1361-6528/aba1b9.
- [23] P. Totzauer and P. Trnka, "Different ways to improve natural ester oils," *Transp. Res. Proc.*, vol. 40, pp. 102–106, Jan. 2019, doi: 10.1016/j.trpro.2019.07.017.
- [24] G. Dombek, P. Gosinski, and Z. Nadolny, "Comparison of mineral oil and esters as cooling liquids in high voltage transformer in aspect of environment protection," in *Proc. E3S Web Conf.*, vol. 14, Mar. 2017, p. 01053, doi: 10.1051/e3sconf/20171401053.
- [25] D. Gnanasekaran and V. P. Chavidi, "Green fluids from vegetable oil: Power plant BT—Vegetable oil based bio-lubricants and transformer fluids: Applications in power plants," in *Vegetable Oil based Bio-lubricants and Transformer Fluids*. Singapore: Springer, 2018.
- [26] M. Rafiq, Y. Z. Lv, Y. Zhou, K. B. Ma, W. Wang, C. R. Li, and Q. Wang, "Use of vegetable oils as transformer oils—A review," *Renew. Sustain. Energy Rev.*, vol. 52, pp. 308–324, Dec. 2015, doi: 10.1016/j.rser.2015.07.032.
- [27] D. M. Mehta, P. Kundu, A. Chowdhury, V. K. Lakhiani, and A. S. Jhala, "A review on critical evaluation of natural ester vis-a-vis mineral oil insulating liquid for use in transformers: Part 1," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 2, pp. 873–880, Apr. 2016, doi: 10.1109/TDEL.2015.005370.
- [28] S. A. Azli, M. H. F. Rahiman, Z. M. Yusoff, N. F. Razali, S. S. A. Wahid, and M. S. Ramli, "A review on alternative oils as dielectric insulating fluids on power transformer," in *Proc. IEEE 15th Int. Colloq. Signal Process. Its Appl. (CSPA)*, Mar. 2019, pp. 198–201, doi: 10.1109/CSPA.2019.8695983.
- [29] S. Bhattacharya, S. Dalai, and B. Chatterjee, "Suitability of alternate fluids as transformer insulation—A comprehensive review," in *Proc. Int. Conf. Comput., Electr. Commun. Eng. (ICCECE)*, Jan. 2020, pp. 1–6, doi: 10.1109/ICCECE48148.2020.9223086.
- [30] D. K. Mahanta, "Green transformer oil: A review," in *Proc. IEEE Int. Conf. Environ. Elect. Eng., IEEE Ind. Commercial Power Syst. Eur.*, Jun. 2020, pp. 1–6, doi: 10.1109/EEEIC/ICPSEurope49358.2020.9160654.
- [31] J. Ren, X. Fu, W. Wang, X. Wang, and W. Liu, "Development, performance and prospect of natural ester insulating oil," *Mocaxue Xuebao/Tribol.*, vol. 40, no. 1, pp. 135–142, 2020, doi: 10.16078/j.tribology.2019087.
- [32] M. Danikas and R. Sarathi, "Alternative fluids—With a particular emphasis on vegetable oils—As replacements of transformer oil: A concise review," *Eng., Technol. Appl. Sci. Res.*, vol. 10, no. 6, pp. 6570–6577, Dec. 2020, doi: 10.48084/etasr.3943.
- [33] I. Chronis, S. Kalogeropoulou, and C. S. Psomopoulos, "A review on the requirements for environmentally friendly insulating oils used in high-voltage equipment under the eco design framework," *Environ. Sci. Pollut. Res.*, vol. 28, no. 26, pp. 33828–33836, Jul. 2021, doi: 10.1007/s11356-020-09601-7.
- [34] M. S. Mohamad, H. Zainuddin, S. A. Ghani, and I. S. Chairul, "AC breakdown voltage of natural ester mixed with iron oxide for oil-immersed power transformer application," in *Proc. IEEE Student Conf. Res. Develop. (SCOREd)*, Dec. 2015, pp. 16–20, doi: 10.1109/SCORED.2015.7449315.
- [35] S. N. Suhaimi, A. R. A. Rahman, M. F. M. Din, M. Z. Hassan, M. T. Ishak, and M. T. B. Jusoh, "A review on oil-based nanofluid as next-generation insulation for transformer application," *J. Nanomater.*, vol. 2020, pp. 1–17, Feb. 2020, doi: 10.1155/2020/2061343.
- [36] J. Fal, O. Mahian, and G. Żyła, "Nanofluids in the service of high voltage transformers: Breakdown properties of transformer oils with nanoparticles, a review," *Energies*, vol. 11, no. 11, p. 2942, 2018, doi: 10.3390/en11112942.
- [37] M. Šárpataky, J. Kurimský, and M. Rajňák, "Dielectric fluids for power transformers with special emphasis on biodegradable nanofluids," *Nanomaterials*, vol. 11, no. 11, p. 2885, Oct. 2021, doi: 10.3390/nano11112885.
- [38] N. A. Azizie and N. Hussin, "Preparation of vegetable oil-based nanofluid and studies on its insulating property: A review," in *Proc. J. Phys., Conf.*, 2020, vol. 1432, no. 1, Art. no. 012025, doi: 10.1088/1742-6596/1432/1/012025.
- [39] World Trade Organization Technical Barriers to Trade (TBT) Committee, *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus*, Standard ASTM D6871, 2017, vol. 10, no. 3, p. 4.
- [40] E. Beran, "Experience with evaluating biodegradability of lubricating base oils," *Tribol. Int.*, vol. 41, no. 12, pp. 1212–1218, Dec. 2008, doi: 10.1016/j.triboint.2008.03.003.
- [41] P. Mercurio, K. A. Burns, and A. Negri, "Testing the ecotoxicology of vegetable versus mineral based lubricating oils: 1. Degradation rates using tropical marine microbes," *Environ. Pollut.*, vol. 129, no. 2, pp. 165–173, May 2004, doi: 10.1016/j.envpol.2003.11.001.
- [42] M. Molnar, L. Leitgib, K. Gruiz, E. Fenyvesi, N. Szaniszló, J. Szejtli, and F. Fava, "Enhanced biodegradation of transformer oil in soils with cyclodextrin—From the laboratory to the field," *Biodegradation*, vol. 16, no. 2, pp. 159–168, Mar. 2005, doi: 10.1007/s10532-004-4873-0.
- [43] I. Siti Afida, G. Razmah, S. K. Yeong, and A. H. Hazimah, "Biodegradability of palm-based lubricants," *J. Oil Palm Res.*, vol. 27, no. 4, pp. 425–432, 2015.
- [44] V. Gibon, "Palm oil and palm kernel oil refining and fractionation technology," in *Palm Oil*. Amsterdam, The Netherlands: Elsevier, 2012, ch. 12, pp. 329–375, doi: 10.1016/B978-0-9818936-9-3.50015-0.
- [45] J. Hwang, Y. Jung, and C. Bae, "Spray and combustion of waste cooking oil biodiesel in a compression-ignition engine," *Int. J. Engine Res.*, vol. 16, no. 5, pp. 664–679, Aug. 2015, doi: 10.1177/1468087415585282.
- [46] K. J. Sinu, "Transformer less high efficiency MOSFET inverter with H6-type configuration for photovoltaic applications," *i-Manager's J. Elect. Eng.*, vol. 7, no. 4, pp. 17–22, Jun. 2014, doi: 10.26634/jee.7.4.2869.
- [47] A. A. Ali and I. G. A. Jalal, "The sustainability related opportunities and challenges with various transformer insulation fluids and business case on re-refining," M.S. thesis, KTH Roy. Inst. Technol., 2017, pp. 1–52.
- [48] N. A. A. Hassan, S. H. M. Fauzi, and Y. S. Kian, "Potential of palm oil waste for biolubricant," *Palm Oil Develop.*, vol. 68, no. 68, pp. 18–21, 2018.
- [49] V. I. Otti, H. I. Ifeanyichukwu, F. C. Nwaorun, and F. U. Ogbuagu, "Sustainable oil palm waste management in engineering development," *Civil Environ. Res.*, vol. 6, no. 5, pp. 121–125, 2014.
- [50] N. Abdullah and F. Sulaim, "The oil palm wastes in Malaysia," in *Biomass Now-Sustainable Growth and Use*. Rijeka, Croatia: InTech, 2013, doi: 10.5772/55302.

- [51] M. Foata and J. B. Dastous, "Power transformer tank rupture prevention," in *Proc. 43rd Int. Conf. Large High Voltage Electr. Syst. (CIGRE)*, France, 2010.
- [52] H. P. Berg and N. Fritze, "Reliability of main transformers," *Rel., Theory Appl.*, vol. 6, nos. 1–20, pp. 52–69, 2011.
- [53] CIGRE Working Group A2.37, *Transformer Reliability Survey*, Cigre, Paris, France, 2015.
- [54] M. El-Harbawi, "Fire and explosion risks and consequences in electrical substations—A transformer case study," *ASME Open J. Eng.*, vol. 1, Jan. 2022, Art. no. 014501, doi: [10.1115/1.4054143](https://doi.org/10.1115/1.4054143).
- [55] Iran Prado Arantes and Geraldo Nicola. (Dec. 23, 2019). *Mitigating Failure Risk in Power Transformers: Eletronorte Case Study*. Transformer Technology. Accessed: Feb. 22, 2022. [Online]. Available: <https://www.transformer-technology.com/news/us-news/964-mitigating-failure-risk-in-power-transformers-eletronorte-case-study-transformer-technology-issue-4.html>
- [56] *Power Installations Exceeding 1 kV AC and 1.5 kV DC*, Standard 61010-1 IEC:2001. International Electrotechnical Commission, Standard IEC 61936-1, 2021, p. 245.
- [57] D. M. Mehta, P. Kundu, A. Chowdhury, V. K. Lakhiani, and A. S. Jhala, "A review of critical evaluation of natural ester vis-a-vis mineral oil insulating liquid for use in transformers: Part II," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 3, pp. 1705–1712, Jun. 2016, doi: [10.1109/TDEL.2016.005371](https://doi.org/10.1109/TDEL.2016.005371).
- [58] "Malaysian palm oil output," *Focus Surfactants*, vol. 2005, no. 4, pp. 2–3, Apr. 2005, doi: [10.1016/S1351-4210\(05\)70698-3](https://doi.org/10.1016/S1351-4210(05)70698-3).
- [59] *Food and Agriculture Organization of the United Nations*, FAOSTAT, Rome, Italy, 2012.
- [60] G. Mrema, "Small-scale palm oil processing in Africa," in *FAO Agricultural Services Bulletin*, vol. 148, Rome, Italy: Food and Agriculture Organization of the United Nations, 2002.
- [61] E. J. Behrman and V. Gopalan, "Cholesterol and plants," *J. Chem. Educ.*, vol. 82, no. 12, p. 1791, Dec. 2005, doi: [10.1021/ed082p1791](https://doi.org/10.1021/ed082p1791).
- [62] B. Nagendran, U. R. Unnithan, Y. M. Choo, and K. Sundram, "Characteristics of red palm oil, a carotene- and vitamin E-rich refined oil for food uses," *Food Nutrition Bull.*, vol. 21, no. 2, pp. 189–194, Jan. 2000, doi: [10.1177/156482650002100213](https://doi.org/10.1177/156482650002100213).
- [63] F. Shahidi, *Bailey's Industrial Oil and Fat Products*. Hoboken, NJ, USA: Wiley, 2005, doi: [10.1002/047167849X](https://doi.org/10.1002/047167849X).
- [64] *Palm Oil Continues to Dominate Global Consumption in 2006/07*, United States Department of Agriculture, Washington, DC, USA, 2006.
- [65] B. Matthäus, "Use of palm oil for frying in comparison with other high-stability oils," *Eur. J. Lipid Sci. Technol.*, vol. 109, no. 4, pp. 400–409, Apr. 2007, doi: [10.1002/ejlt.200600294](https://doi.org/10.1002/ejlt.200600294).
- [66] Y. B. C. Man, J. L. Liu, B. Jamilah, and R. A. Rahman, "Quality changes of refined-bleached-deodorized (RBD) palm olein, soybean oil and their blends during deep-fat frying," *J. Food Lipids*, vol. 6, no. 3, pp. 181–193, Sep. 1999, doi: [10.1111/j.1745-4522.1999.tb00142.x](https://doi.org/10.1111/j.1745-4522.1999.tb00142.x).
- [67] Y. B. C. Man, T. Haryati, H. M. Ghazali, and B. A. Asbi, "Composition and thermal profile of crude palm oil and its products," *J. Amer. Oil Chemists' Soc.*, vol. 76, no. 2, pp. 237–242, Feb. 1999, doi: [10.1007/s11746-999-0224-y](https://doi.org/10.1007/s11746-999-0224-y).
- [68] O. M. Lai, H. M. Ghazali, and C. L. Chong, "Physical properties of Pseudomonas and Rhizomucor miehei lipase-catalyzed transesterified blends of palm stearin: Palm kernel olein," *J. Amer. Oil Chemists' Soc.*, vol. 75, no. 8, pp. 953–959, Aug. 1998, doi: [10.1007/s11746-998-0272-8](https://doi.org/10.1007/s11746-998-0272-8).
- [69] N. A. Ibrahim, "Characteristics of Malaysian palm kernel and its products," *J. Oil Palm Res.*, vol. 25, no. 2, pp. 245–252, Aug. 2013.
- [70] *Vegetable Oil Transformer for Ultra-High Voltages*, T&D World, USA, Aug. 2013.
- [71] World Trade Organization Technical Barriers to Trade (TBT) Committee, *Standart Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using VDE Electrodes*, Standard ASTM D1816-12, 2019.
- [72] IEC, *Insulating Liquids—Determination of the Breakdown Voltage at Power Frequency—Test Method*, Edition 3.0., Standard IEC 60156, 2018.
- [73] N. K. Mohd, L. Wen-Huei, N. A. A. Hassan, and Y. Shoot-Kian, "Potential application of palm oil products as electrical insulating medium in oil-immersed transformers," *Environ. Prog. Sustain. Energy*, vol. 40, no. 6, Nov. 2021, Art. no. e13728, doi: [10.1002/ep.13728](https://doi.org/10.1002/ep.13728).
- [74] S. Ravulapalli, R. Kunta, and M. Ramamoorthy, "Preparation, characterization and feasibility analysis of methyl ester of sesbania seeds oil (MESSO) as alternate liquid dielectrics in distribution transformers," *RSC Adv.*, vol. 9, no. 6, pp. 3311–3319, Jan. 2019, doi: [10.1039/C8RA08378A](https://doi.org/10.1039/C8RA08378A).
- [75] J.-B. Asse, G. M. Mengounou, and A. M. Imano, "Impact of FeO₃ on the AC breakdown voltage and acidity index of a palm kernel oil methyl ester based nanofluid," *Energy Rep.*, vol. 8, pp. 275–280, Nov. 2022, doi: [10.1016/j.egy.2021.11.291](https://doi.org/10.1016/j.egy.2021.11.291).
- [76] A. A. Abdelmalik, J. C. Fothergill, and S. J. Dodd, "Electrical breakdown strength characteristics of palm kernel oil ester-based dielectric fluids," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectric Phenomena*, Oct. 2011, pp. 183–186, doi: [10.1109/CEIDP.2011.6232627](https://doi.org/10.1109/CEIDP.2011.6232627).
- [77] T. Kanoh, H. Iwabuchi, Y. Hoshida, J. Yamada, T. Hikosaka, A. Yamazaki, Y. Hatta, and H. Koide, "Analyses of electro-chemical characteristics of palm fatty acid esters as insulating oil," in *Proc. IEEE Int. Conf. Dielectric Liquids*, Jun. 2008, pp. 1–4, doi: [10.1109/ICDL.2008.4622456](https://doi.org/10.1109/ICDL.2008.4622456).
- [78] T. Kano, T. Suzuki, R. Oba, A. Kanetani, and H. Koide, "Study on the oxidative stability of palm fatty acid ester (PFAE) as an insulating oil for transformers," in *Proc. IEEE Int. Symp. Electr. Insul.*, Jun. 2012, pp. 22–25, doi: [10.1109/ELINSL.2012.6251418](https://doi.org/10.1109/ELINSL.2012.6251418).
- [79] M. S. Mohamad, H. Zainuddin, S. A. Ghani, and I. S. Chairul, "AC breakdown voltage and viscosity of palm fatty acid ester (PFAE) oil-based nanofluids," *J. Elect. Eng. Technol.*, vol. 12, no. 6, pp. 2333–2341, 2017, doi: [10.5370/JEET.2017.12.6.2333](https://doi.org/10.5370/JEET.2017.12.6.2333).
- [80] M. S. Mohamad, H. Zainuddin, S. A. Ghani, and I. S. Chairul, "Breakdown and partial discharge performance of palm fatty acid ester (PFAE) oil-based Fe₃O₄ nanofluids," Nov. 2017, pp. 317–321, doi: [10.1109/PECON.2016.7951580](https://doi.org/10.1109/PECON.2016.7951580).
- [81] S. S. A. Ghani and N. A. Muhamad, "Hydrocarbon gases dissolved in palm-based insulation oil after experienced breakdown," in *Proc. IEEE 11th Int. Conf. Properties Appl. Dielectric Mater. (ICPADM)*, Jul. 2015, pp. 460–463, doi: [10.1109/ICPADM.2015.7295308](https://doi.org/10.1109/ICPADM.2015.7295308).
- [82] M. Yaacob and M. Alsaedi, "Use palm oil as alternative with insulation oil in high voltage equipment," *Phys. Sci. Int. J.*, vol. 5, no. 3, pp. 172–178, Jan. 2015, doi: [10.9734/PSIJ/2015/12790](https://doi.org/10.9734/PSIJ/2015/12790).
- [83] S. Aditama, "Dielectric properties of palm oils as liquid insulating materials: Effects of fat content," in *Proc. Int. Symp. Electr. Insulating Mater. (ISEIM)*, 2005, pp. 91–94, doi: [10.1109/ISEIM.2005.193334](https://doi.org/10.1109/ISEIM.2005.193334).
- [84] N. S. Suhaimi, M. F. Md Din, C. Y. Tan, M. T. Ishak, A. R. B. A. Rahman, W. F. H. Wan Zambri, and J. L. Wang, "Electrical properties and Raman scattering of palm oil based carbon nanotube," *Key Eng. Mater.*, vol. 908, pp. 343–347, Jan. 2022, doi: [10.4028/p-25v391](https://doi.org/10.4028/p-25v391).
- [85] M. F. M. Din, N. S. Mazlan, A. R. B. A. Rahman, M. T. Jusoh, N. S. Suhaimi, and F. R. Hashim, "Investigation on the dielectric properties of palm oil with silicon carbide doping for transformer application," *Solid State Phenomena*, vol. 317, pp. 377–382, May 2021, doi: [10.4028/www.scientific.net/SSP.317.377](https://doi.org/10.4028/www.scientific.net/SSP.317.377).
- [86] M. R. Ahmed, M. S. Islm, and A. K. Karmaker, "Experimental investigation of electrical and thermal properties of vegetable oils for used in transformer," in *Proc. Int. Conf. Autom., Control Mechatronics Ind. 4.0 (ACMI)*, Jul. 2021, pp. 1–4, doi: [10.1109/ACMI53878.2021.9528278](https://doi.org/10.1109/ACMI53878.2021.9528278).
- [87] M. H. A. Hamid, M. T. Ishak, N. S. Suhaimi, J. Adnan, N. I. Hashim, M. Ariffin, N. I. A. Katim, and R. Abd Rahman, "Electrical properties of palm oil and Rice bran oil under AC stress for transformer application," *Alexandria Eng. J.*, vol. 61, no. 11, pp. 9095–9105, Nov. 2022, doi: [10.1016/j.aej.2022.02.049](https://doi.org/10.1016/j.aej.2022.02.049).
- [88] K. Wajanasoonthon and A. Suksri, "Electrical breakdown voltage of palm oil and nano graphene filler in nanofluids application on transformer insulating oil," *Key Eng. Mater.*, vol. 902, pp. 59–63, Oct. 2021, doi: [10.4028/www.scientific.net/KEM.902.59](https://doi.org/10.4028/www.scientific.net/KEM.902.59).
- [89] G. O. Boyekong, G. M. Mengounou, and A. M. Imano, "Comparative evaluation of the thermal aging of solid insulation in mineral oil and methyl ester of palm kernel oil," *J. Power Energy Eng.*, vol. 9, no. 5, pp. 166–183, 2021, doi: [10.4236/jpee.2021.95010](https://doi.org/10.4236/jpee.2021.95010).
- [90] S. O. Oparanti, A. A. Khaleed, and A. A. Abdelmalik, "AC breakdown analysis of synthesized nanofluids for oil-filled transformer insulation," *Int. J. Adv. Manuf. Technol.*, vol. 117, nos. 5–6, pp. 1395–1403, Nov. 2021, doi: [10.1007/s00170-021-07631-0](https://doi.org/10.1007/s00170-021-07631-0).
- [91] N. A. Mohamad, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, and Z. Yaakub, "Impact of Fe₃O₄, CuO and Al₂O₃ on the AC breakdown voltage of palm oil and coconut oil in the presence of CTAB," *Energies*, vol. 12, no. 9, p. 1605, Apr. 2019, doi: [10.3390/en12091605](https://doi.org/10.3390/en12091605).
- [92] Y. E. Sari, T. I. D. K. Dewi, and S. Suwarno, "The effects of electrical arc aging on dielectric properties and partial discharge patterns of natural ester from palm oil," in *Proc. 2nd Int. Conf. High Voltage Eng. Power Syst. (ICHVEPS)*, Oct. 2019, pp. 1–5, doi: [10.1109/ICHVEPS47643.2019.9011053](https://doi.org/10.1109/ICHVEPS47643.2019.9011053).

- [93] N. D. Ahmad, N. M. S. N. Omar, S. S. M. Ramli, N. H. Ishak, M. T. Ishak, and N. M. Zain, "A study on varies temperature and varies gap distance on mixed vegetable oil as a transformer oil," in *Proc. 4th Int. Conf. Workshops Recent Adv. Innov. Eng. (ICRAIE)*, Nov. 2019, pp. 1–4, doi: [10.1109/ICRAIE47735.2019.9037774](https://doi.org/10.1109/ICRAIE47735.2019.9037774).
- [94] M. Bakruthen, M. W. Iruthayarajan, and A. Narayani, "Statistical failure reliability analysis on edible and non edible natural esters based liquid insulation for the applications in high voltage transformers," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 5, pp. 1579–1586, Oct. 2018, doi: [10.1109/TDEI.2018.006628](https://doi.org/10.1109/TDEI.2018.006628).
- [95] N. D. Ahmad, S. N. M. Zubir, S. S. Ramli, N. H. Ishak, W. S. Saidon, and N. A. Salim, "A study of palm oil as an insulating medium," *Int. J. Eng. Technol.*, vol. 7, no. 4, pp. 17–20, 2018.
- [96] N. S. Suhaimi, M. F. M. Din, M. T. Ishak, and A. R. A. Rahman, "Statistical analysis on AC breakdown voltage of CNT nanofluid with mineral oil and palm oil," in *Proc. IEEE 7th Int. Conf. Power Energy (PECon)*, Dec. 2018, pp. 111–116, doi: [10.1109/PECON.2018.8684081](https://doi.org/10.1109/PECON.2018.8684081).
- [97] N. A. M. Amin, M. T. Ishak, J. Adnan, M. T. Jusoh, and F. Ridzuan, "AC breakdown voltage and dielectric properties of palm oil as insulating liquid with the presence of copper particles," in *Proc. IEEE 7th Int. Conf. Power Energy (PECon)*, Dec. 2018, doi: [10.1109/PECON.2018.8684149](https://doi.org/10.1109/PECON.2018.8684149).
- [98] M. B. Yahya and F. A. B. Amirrazli, "Study of breakdown voltage of vegetables oil with SiO₂ nanoparticle additive," *Indonesian J. Electr. Eng. Comput. Sci.*, vol. 12, no. 1, p. 296, Oct. 2018, doi: [10.11591/ijeecs.v12.i1.pp296-302](https://doi.org/10.11591/ijeecs.v12.i1.pp296-302).
- [99] I. S. Chairul, N. A. Bakar, M. N. Othman, S. A. Ghani, and M. N. Deraman, "Development of waste cooking oil methyl esteras potential electrical insulating fluid for power transformer," *ARPN J. Eng. Appl. Sci.*, vol. 13, no. 20, pp. 8154–8162, 2018.
- [100] N. I. A. Katim, M. T. Ishak, N. A. M. Amin, S. Razali, M. H. A. Hamid, M. M. Ariffin, and N. Azis, "Investigation on AC breakdown of vegetable oils with insulated electrodes," in *Proc. Int. Conf. High Voltage Eng. Power Syst. (ICHVEPS)*, Oct. 2017, pp. 312–316, doi: [10.1109/ICHVEPS.2017.8225963](https://doi.org/10.1109/ICHVEPS.2017.8225963).
- [101] M. H. A. Hamid, M. T. Ishak, M. M. Ariffin, N. I. A. Katim, N. A. M. Amin, and N. Azis, "Dissolved gas analysis (DGA) of vegetable oils under electrical stress," in *Proc. Int. Conf. High Voltage Eng. Power Syst. (ICHVEPS)*, Oct. 2017, pp. 29–34, doi: [10.1109/ICHVEPS.2017.8225862](https://doi.org/10.1109/ICHVEPS.2017.8225862).
- [102] M. H. A. Hamid, M. T. Ishak, M. F. M. Din, N. S. Suhaimi, and N. I. A. Katim, "Dielectric properties of natural ester oils used for transformer application under temperature variation," in *Proc. IEEE Int. Conf. Power Energy (PECon)*, Nov. 2016, pp. 54–57, doi: [10.1109/PECON.2016.7951472](https://doi.org/10.1109/PECON.2016.7951472).
- [103] S. F. M. Nor, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, M. T. Ishak, and Z. Yaakub, "A study on the AC breakdown voltages of as-received palm oil and coconut oil under presence of TiO₂," in *Proc. IEEE Conf. Energy Convers. (CENCON)*, Oct. 2015, pp. 354–357, doi: [10.1109/CENCON.2015.7409568](https://doi.org/10.1109/CENCON.2015.7409568).
- [104] S. S. Sinan, S. N. Shawaludin, J. Jasni, N. Azis, M. Z. A. A. Kadir, and M. N. Mohtar, "Investigation on the AC breakdown voltage of RBDPO olein," in *Proc. IEEE Innov. Smart Grid Technol.-Asia (ISGT ASIA)*, May 2014, pp. 760–763, doi: [10.1109/ISGT-Asia.2014.6873888](https://doi.org/10.1109/ISGT-Asia.2014.6873888).
- [105] A. A. Abdelmalik, J. C. Fothergill, and S. J. Dodd, "Electrical properties of ester dielectric fluids from palm kernel oil," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectric Phenomena*, Oct. 2011, pp. 415–418, doi: [10.1109/CEIDP.2011.6232683](https://doi.org/10.1109/CEIDP.2011.6232683).
- [106] K. Azmi, M. K. M. Jamil, and M. A. Ahmad, "Breakdown voltage characteristics of RBD palm olein and envirotemp FR3 mixture under quasi-uniform electric field," in *Proc. IEEE Colloq. Humanities, Sci. Eng.*, Dec. 2011, pp. 421–424, doi: [10.1109/CHUSER.2011.6163764](https://doi.org/10.1109/CHUSER.2011.6163764).
- [107] A. Rajab and S. Aminuddin, "Properties of RBDPO oleum as a candidate of palm based-transformer insulating liquid," in *Proc. Int. Conf. Electr. Eng. Inform.*, Aug. 2009, pp. 548–552, doi: [10.1109/ICEEI.2009.5254755](https://doi.org/10.1109/ICEEI.2009.5254755).
- [108] I. S. Darma, "Dielectric properties of mixtures between mineral oil and natural ester," in *Proc. Int. Symp. Electr. Insulating Mater. (ISEIM)*, Sep. 2008, pp. 514–517, doi: [10.1109/ISEIM.2008.4664471](https://doi.org/10.1109/ISEIM.2008.4664471).
- [109] F. Sitinjak, I. Suhariadi, and L. Imsak, "Study on the characteristics of palm oil and it's derivatives as liquid insulating materials," in *Proc. 7th Int. Conf. Properties Appl. Dielectric Mater.*, 2003, pp. 495–498, doi: [10.1109/ICPADM.2003.1218461](https://doi.org/10.1109/ICPADM.2003.1218461).
- [110] B. A. Tlhabologo, R. Samikannu, and M. Mosalaosi, "Alternative liquid dielectrics in power transformer insulation: A review," *Indonesian J. Electr. Eng. Comput. Sci.*, vol. 23, no. 3, p. 1761, Sep. 2021, doi: [10.11591/ijeecs.v23.i3.pp1761-1777](https://doi.org/10.11591/ijeecs.v23.i3.pp1761-1777).
- [111] G. Dombek, Z. Nadolny, and P. Przybylek, "The study of thermal properties of mineral oil and synthetic ester modified by nanoparticles TiO₂ and C₆₀," in *Proc. ICHVE Int. Conf. High Voltage Eng. Appl.*, Sep. 2014, pp. 1–4, doi: [10.1109/ICHVE.2014.7035466](https://doi.org/10.1109/ICHVE.2014.7035466).
- [112] *Electrical Strength of Insulating Materials—Test Methods—Part 1: Tests at Power Frequencies*, International Standard, Standard IEC 60243-1, 2004.
- [113] S. F. M. Nor, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, and Z. Yaakub, "Investigation on the electrical properties of palm oil and coconut oil based TiO₂ nanofluids," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 6, pp. 3432–3442, Dec. 2017, doi: [10.1109/TDEI.2017.006295](https://doi.org/10.1109/TDEI.2017.006295).
- [114] N. S. Suhaimi, M. F. M. Din, M. T. Ishak, A. R. A. Rahman, M. M. Ariffin, N. I. Hashim, and J. Wang, "Systematical study of multi-walled carbon nanotube nanofluids based disposed transformer oil," *Sci. Rep.*, vol. 10, no. 1, p. 20984, Dec. 2020, doi: [10.1038/s41598-020-77810-8](https://doi.org/10.1038/s41598-020-77810-8).
- [115] P. Dhar, A. Katiyar, L. S. Maganti, A. Pattamatta, and S. K. Das, "Superior dielectric breakdown strength of graphene and carbon nanotube infused nano-oils," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 2, pp. 943–956, Apr. 2016, doi: [10.1109/TDEI.2015.005477](https://doi.org/10.1109/TDEI.2015.005477).
- [116] N. S. Suhaimi, M. T. Ishak, M. F. Din, M. M. Ariffin, S. Razali, N. A. Amin, and F. R. Hashim, "Breakdown strength of transformer oil filled with carbon nanotubes under various gap distances," *J. Fundam. Appl. Sci.*, vol. 9, no. 3S, p. 41, Jan. 2018, doi: [10.4314/jfas.v9i3s.4](https://doi.org/10.4314/jfas.v9i3s.4).
- [117] N. S. Suhaimi, M. F. M. Din, A. R. A. Rahman, M. H. A. Hamid, N. A. M. Amin, W. F. H. W. Zamri, and J. Wang, "Optimum electrical and dielectric performance of multi-walled carbon nanotubes doped disposed transformer oil," *Energies*, vol. 13, no. 12, p. 3181, Jun. 2020, doi: [10.3390/en13123181](https://doi.org/10.3390/en13123181).
- [118] A. H. A. Al-Waeli, M. T. Chaichan, H. A. Kazem, and K. Sopian, "Evaluation and analysis of nanofluid and surfactant impact on photovoltaic-thermal systems," *Case Stud. Thermal Eng.*, vol. 13, Mar. 2019, Art. no. 100392, doi: [10.1016/j.csite.2019.100392](https://doi.org/10.1016/j.csite.2019.100392).
- [119] M. Jang, "The potential power of graphene," *Student Int. J. Res.*, vol. 1454, no. 3, pp. 1–12, 2016.
- [120] Y. Zhang, Y.-R. Leu, R. Aitken, and M. Riediker, "Inventory of engineered nanoparticle-containing consumer products available in the Singapore retail market and likelihood of release into the aquatic environment," *Int. J. Environ. Res. Public Health*, vol. 12, no. 8, pp. 8717–8743, Jul. 2015, doi: [10.3390/ijerph120808717](https://doi.org/10.3390/ijerph120808717).
- [121] P. Muangpratoom, "The effect of temperature on the electrical characteristics of nanofluids based on palm oil," *J. Eng. Technol. Sci.*, vol. 53, no. 3, Jul. 2021, Art. no. 210312, doi: [10.5614/j.eng.technol.sci.2021.53.3.12](https://doi.org/10.5614/j.eng.technol.sci.2021.53.3.12).
- [122] M. Z. H. Makmud, H. A. Illias, C. Y. Chee, and M. S. Sarjadi, "Influence of conductive and semi-conductive nanoparticles on the dielectric response of natural ester-based nanofluid insulation," *Energies*, vol. 11, no. 2, p. 333, 2018, doi: [10.3390/en11020333](https://doi.org/10.3390/en11020333).
- [123] W. Saenkhumwong and A. Suk Sri, "The improved dielectric properties of natural ester oil by using ZnO and TiO₂ nanoparticles," *Eng. Appl. Sci. Res.*, vol. 44, no. 3, pp. 148–153, 2017, doi: [10.14456/ear.2017.22](https://doi.org/10.14456/ear.2017.22).
- [124] Z. Sharafi, B. Bakhshi, J. Javidi, and S. Adrangi, "Synthesis of silica-coated iron oxide nanoparticles: Preventing aggregation without using additives or seed pretreatment," *Iranian J. Pharmaceutical Res.*, vol. 17, no. 1, p. 386, 2018.
- [125] J. Chen, P. Sun, W. Sima, Q. Shao, L. Ye, and C. Li, "A promising nano-insulating-oil for industrial application: Electrical properties and modification mechanism," *Nanomaterials*, vol. 9, no. 5, p. 788, May 2019, doi: [10.3390/nano9050788](https://doi.org/10.3390/nano9050788).
- [126] Z. Taghikhani, M. A. Taghikhani, and G. B. Gharehpetian, "Mineral oil based CuO nanofluid-immersed transformers analysis concerning the efficacy of nanocrystalline alloy core in reduction of losses and HST," *J. Magn. Magn. Mater.*, vol. 537, Nov. 2021, Art. no. 168184, doi: [10.1016/j.jmmm.2021.168184](https://doi.org/10.1016/j.jmmm.2021.168184).
- [127] S. Asthana, S. Rattan, and M. Das, "Comparative studies of copper oxide with aluminium oxide nanoparticles in conventional thermal fluids for its enhanced efficiency as coolant," *Proc. Nat. Acad. Sci., India A, Phys. Sci.*, vol. 83, no. 2, pp. 73–77, Jun. 2013, doi: [10.1007/s40010-012-0057-1](https://doi.org/10.1007/s40010-012-0057-1).

- [128] R. R. Meena, S. H. Chaki, A. J. Khimani, and M. P. Deshpande, "Investigation of ultrasonic parameters and measurement of thermal conductivity of CuO-transformer oil nanofluids," *Mater. Res. Exp.*, vol. 6, no. 8, Jun. 2019, Art. no. 0850f3, doi: [10.1088/2053-1591/ab2754](https://doi.org/10.1088/2053-1591/ab2754).
- [129] N. A. Mohamad, N. Azis, J. Jasni, R. Yunus, M. Z. A. A. Kadir, and Z. Yaakub, "Effects of different types of surfactants on AC breakdown voltage of refined, bleached and deodorized palm oil based CuO nanofluids," in *Proc. IEEE PES Asia-Pacific Power Energy Eng. Conf. (APPEEC)*, Oct. 2018, pp. 768–771, doi: [10.1109/APPEEC.2018.8566559](https://doi.org/10.1109/APPEEC.2018.8566559).
- [130] M. Bakruthen, R. Karthik, and R. Madavan, "Investigation of critical parameters of insulating mineral oil using semiconductive nanoparticles," in *Proc. Int. Conf. Circuits, Power Comput. Technol. (ICCPCT)*, Mar. 2013, pp. 294–299, doi: [10.1109/ICCPCT.2013.6529039](https://doi.org/10.1109/ICCPCT.2013.6529039).
- [131] M. Hanai, S. Hosomi, H. Kojima, N. Hayakawa, and H. Okubo, "Dependence of TiO₂ and ZnO nanoparticle concentration on electrical insulation characteristics of insulating oil," in *Proc. Annu. Rep. Conf. Elect. Insul. Dielectric Phenomena*, Oct. 2013, pp. 780–783, doi: [10.1109/CEIDP.2013.6748164](https://doi.org/10.1109/CEIDP.2013.6748164).
- [132] H. Duzkaya and A. Beroual, "Statistical analysis of AC dielectric strength of natural ester-based ZnO nanofluids," *Energies*, vol. 14, no. 1, p. 99, Dec. 2020, doi: [10.3390/en14010099](https://doi.org/10.3390/en14010099).
- [133] N. Hussin, N. A. Subri, N. A. Azizie, A. N. M. Khalil, M. K. M. Jamil, R. Abd-Rahman, and S. N. M. Arshad, "Low concentration vegetable oil based nanofluid: Dielectric properties, AC breakdown voltage and kinematic viscosity," in *Proc. J. Phys., Conf.*, 2021, vol. 1878, no. 1, Art. no. 012037, doi: [10.1088/1742-6596/1878/1/012037](https://doi.org/10.1088/1742-6596/1878/1/012037).
- [134] A. Jean-Bernard, M. M. Ghislain, and M. I. Adolphe, "Investigation of the effect of zinc nanoparticles (Zn) on the AC breakdown voltage and acidity index of based nanofluid on methyl ester of palm kernel oil," *Int. J. Sci. Technol. Res.*, vol. 10, no. 6, pp. 262–267, Jul. 2021.
- [135] M. A. H. M. Sohor, M. Mustapha, and J. C. Kurnia, "Silicon carbide-from synthesis to application: A review," in *Proc. MATEC Web Conf.*, vol. 131, Oct. 2017, p. 04003, doi: [10.1051/mateconf/201713104003](https://doi.org/10.1051/mateconf/201713104003).
- [136] D. Dixit, R. Pal, G. Kapoor, and M. Stabenau, "Lightweight composite materials processing," in *Lightweight Ballistic Composites: Military and Law-Enforcement Applications*, 2nd ed. Cambridge, U.K.: Woodhead, 2016, ch. 6, doi: [10.1016/B978-0-08-100406-7.00006-4](https://doi.org/10.1016/B978-0-08-100406-7.00006-4).
- [137] Y. Miyamoto, M. Nakamura, T. Tojo, and W. Chen, *Nanoparticle Technology Handbook*. Oxford, U.K.: Elsevier, 2012.
- [138] H. Jin, T. Andritsch, I. A. Tsekmes, R. Kochetov, P. H. F. Morshuis, and J. J. Smit, "Properties of mineral oil based silica nanofluids," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 3, pp. 1100–1108, Jun. 2014, doi: [10.1109/TDEL.2014.6832254](https://doi.org/10.1109/TDEL.2014.6832254).
- [139] M. Rafiq, D. Khan, and M. Ali, "Insulating properties of transformer oil-based silica nanofluids," in *Proc. Power Gener. Syst. Renew. Energy Technol. (PGSRET)*, Jun. 2015, pp. 1–3, doi: [10.1109/PGSRET.2015.7312201](https://doi.org/10.1109/PGSRET.2015.7312201).
- [140] R. Karthik and A. Raymon, "Effect of silicone oxide nano particles on dielectric characteristics of natural ester," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl. (ICHVE)*, Sep. 2016, pp. 1–3, doi: [10.1109/ICHVE.2016.7800576](https://doi.org/10.1109/ICHVE.2016.7800576).
- [141] A. S. Keiteb, E. Saion, A. Zakaria, and N. Soltani, "Structural and optical properties of zirconia nanoparticles by thermal treatment synthesis," *J. Nanomater.*, vol. 2016, pp. 1–6, May 2016, doi: [10.1155/2016/1913609](https://doi.org/10.1155/2016/1913609).
- [142] N. L. Nwidae, S. Al-Anssari, A. Barifcani, M. Sarmadivaleh, and S. Iglauer, "Nanofluids for enhanced oil recovery processes: Wettability alteration using zirconium oxide," in *Proc. Offshore Technol. Conf. Asia*, Mar. 2016, pp. 1606–1616, doi: [10.4043/26573-MS](https://doi.org/10.4043/26573-MS).
- [143] S. C. Pugazhendhi, "Experimental evaluation on dielectric and thermal characteristics of nano filler added transformer oil," in *Proc. Int. Conf. High Voltage Eng. Appl. (ICHVE)*, Sep. 2012, pp. 207–210, doi: [10.1109/ICHVE.2012.6357077](https://doi.org/10.1109/ICHVE.2012.6357077).
- [144] H. Vaishnav, K. Navin, R. Kurchania, and R. J. Ball, "Synthesis of ZrO₂ based nanofluids for cooling and insulation of transformers," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 29, no. 1, pp. 199–205, Feb. 2022, doi: [10.1109/TDEL.2022.3148444](https://doi.org/10.1109/TDEL.2022.3148444).
- [145] J. G. Hwang, M. Zahn, F. M. O'Sullivan, L. A. A. Pettersson, O. Hjortstam, and R. Liu, "Effects of nanoparticle charging on streamer development in transformer oil-based nanofluids," *J. App. Phys.*, vol. 107, Jan. 2010, Art. no. 014310, doi: [10.1063/1.3267474](https://doi.org/10.1063/1.3267474).
- [146] World Trade Organization Technical Barriers to Trade Committee, *Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids Under Impulse Condition*, Standard ASTM D3300-20, 2020.
- [147] International Electrotechnical Commission, *Methods for the Determination of the Lightning Impulse Breakdown Voltage of Insulating Liquids*, Geneva, Switzerland, Standard IEC 60897, 1987.
- [148] V. A. Primo, B. García, J. C. Burgos, and D. Pérez-Rosa, "Investigation of the lightning impulse breakdown voltage of mineral oil based Fe₃O₄ nanofluids," *Coatings*, vol. 9, no. 12, p. 799, Nov. 2019, doi: [10.3390/coatings9120799](https://doi.org/10.3390/coatings9120799).
- [149] Y. V. Thien, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, M. T. Ishak, and N. R. Hamzah, "A study on the lightning impulse breakdown voltages of palm oil and coconut oil by different methods," *Appl. Mech. Mater.*, vol. 793, pp. 9–13, Sep. 2015, doi: [10.4028/www.scientific.net/amm.793.9](https://doi.org/10.4028/www.scientific.net/amm.793.9).
- [150] Y. V. Thien, N. Azis, J. Jasni, R. Yunus, M. Z. A. A. Kadir, and Z. Yaakub, "Influence of electrode geometry on the lightning impulse breakdown voltage of palm oil," in *Proc. IEEE PES Asia-Pacific Power Energy Eng. Conf. (APPEEC)*, Oct. 2018, pp. 317–320, doi: [10.1109/APPEEC.2018.8566615](https://doi.org/10.1109/APPEEC.2018.8566615).
- [151] V. Y. Ushakov, V. F. Klimkin, and S. M. Korobeynikov, *Impulse Breakdown of Liquids*. Berlin, Germany: Springer, 2007, doi: [10.1007/978-3-540-72760-6](https://doi.org/10.1007/978-3-540-72760-6).
- [152] H. Li, L. Xia, S. Cai, Z. Huang, J. Li, and L. Zhong, "Influence of molecule structure on lightning impulse breakdown of ester liquids," *Energies*, vol. 14, no. 4, p. 1061, Feb. 2021, doi: [10.3390/en14041061](https://doi.org/10.3390/en14041061).
- [153] M. Kamarol, M. Zuhilmey, and Y. A. Arief, "Breakdown characteristics of RBDPO and soybean oil mixture for transformer application," in *Proc. Int. Conf. Electr., Control Comput. Eng. (INECCE)*, Jun. 2011, pp. 219–222, doi: [10.1109/INECCE.2011.5953879](https://doi.org/10.1109/INECCE.2011.5953879).
- [154] M. T. Ishak, M. T. Jusoh, J. Adnan, and R. A. Rahman, "Lightning impulse breakdown voltage RBDPO with the presence of metallic particles under a uniform electric field," *Jurnal Kejuruteraan SI*, vol. 4, no. 2, pp. 127–134, 2021.
- [155] N. A. M. Amin, M. T. Ishak, N. I. A. Katim, M. H. A. Hamid, F. R. Hashim, and M. F. M. Din, "Lightning impulse investigation on vegetables oils and simulation of electric field distribution," *J. Fundam. Appl. Sci.*, vol. 9, no. 3S, p. 373, Jan. 2018, doi: [10.4314/jfas.v9i3s.30](https://doi.org/10.4314/jfas.v9i3s.30).
- [156] Y. V. Thien, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, M. T. Ishak, and Z. Yaakub, "Evaluation on the lightning breakdown voltages of palm oil and coconut oil under non-uniform field at small gap distances," *J. Electr. Eng. Technol.*, vol. 11, no. 1, pp. 184–191, Jan. 2016, doi: [10.5370/JEET.2016.11.1.184](https://doi.org/10.5370/JEET.2016.11.1.184).
- [157] N. I. A. Katim, M. T. Ishak, A. M. Ishak, Y. V. Thein, N. Azis, M. Z. A. A. Kadir, J. Jasni, R. Yunus, and Z. Yaakub, "Examination on the lightning breakdown strength of biodegradable oil under quasi-uniform field," in *Proc. IEEE Int. Conf. Power Energy (PECon)*, Dec. 2014, pp. 17–20, doi: [10.1109/PECON.2014.7062406](https://doi.org/10.1109/PECON.2014.7062406).
- [158] Y. V. Thien, N. Azis, J. Jasni, M. Z. A. A. Kadir, R. Yunus, M. T. Ishak, and Z. Yaakub, "Investigation on the lightning breakdown voltages of palm oil and coconut oil under positive and negative polarities," vol. 72, no. 1, pp. 1–4, 2015.
- [159] D. C. Shill, A. K. Das, and S. Chatterjee, "Insulation and cooling performance of transformer oil based nanofluid," in *Proc. Int. Conf. Comput., Electr. Commun. Eng. (ICCECE)*, Jan. 2020, pp. 1–4, doi: [10.1109/ICCECE48148.2020.9223077](https://doi.org/10.1109/ICCECE48148.2020.9223077).
- [160] M. M. Hessian, N. A. Sabiha, S. S. M. Ghoneim, and A. A. Alahmadi, "Enhancement of dielectric characteristics of transformer oils with nanoparticles," *Int. J. Appl. Eng. Res.*, vol. 12, no. 24, pp. 15668–15673, 2017.
- [161] S. Potvejikul, N. Pattanadech, K. Jariyanurat, and W. Wattakapaiboon, "Electrical characteristics of natural ester based nanofluid," in *Proc. Int. Electr. Eng. Congr. (IEECON)*, Mar. 2017, pp. 1–3, doi: [10.1109/IEECON.2017.8075762](https://doi.org/10.1109/IEECON.2017.8075762).
- [162] Q. Wang, M. Rafiq, Y. Lv, C. Li, and K. Yi, "Preparation of three types of transformer oil-based nanofluids and comparative study on the effect of nanoparticle concentrations on insulating property of transformer oil," *J. Nanotechnol.*, vol. 2016, pp. 1–6, Nov. 2016, doi: [10.1155/2016/5802753](https://doi.org/10.1155/2016/5802753).
- [163] P. Wedin, "Electrical breakdown in dielectric liquids—A short overview," *IEEE Elect. Insul. Mag.*, vol. 30, no. 6, pp. 20–25, Nov. 2014, doi: [10.1109/MEI.2014.6943430](https://doi.org/10.1109/MEI.2014.6943430).

- [164] D. J. Holtzhausen and D. W. Vosloo, *High Voltage Engineering Practice and Theory*. 2003.
- [165] D. K. Mahanta and S. Laskar, "Electrical insulating liquid: A review," *J. Adv. Dielectr.*, vol. 7, no. 4, Aug. 2017, Art. no. 1730001, doi: [10.1142/S2010135X17300018](https://doi.org/10.1142/S2010135X17300018).
- [166] S. K. Hoekman, A. Broch, C. Robbins, E. Cenicerros, and M. Natarajan, "Review of biodiesel composition, properties, and specifications," *Renew. Sustain. Energy Rev.*, vol. 16, no. 1, pp. 143–169, Jan. 2012, doi: [10.1016/j.rser.2011.07.143](https://doi.org/10.1016/j.rser.2011.07.143).
- [167] L. R. Lewand, "Laboratory testing of natural ester dielectric liquids," Neta World, Tech. Rep., 2004.
- [168] S. M. Yusof, N. Hussin, and M. Isa, "Viscosity reduction of palm oil via ultrasonic radiation," *Appl. Mech. Mater.*, vol. 785, pp. 315–319, Aug. 2015, doi: [10.4028/www.scientific.net/AMM.785.315](https://doi.org/10.4028/www.scientific.net/AMM.785.315).
- [169] M. Bakruthen, M. W. Iruthayarajan, and A. Narayani, "Influence of ultrasonic waves on viscosity of edible natural esters based liquid insulation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 5, pp. 1628–1635, Oct. 2018, doi: [10.1109/TDEI.2018.006931](https://doi.org/10.1109/TDEI.2018.006931).
- [170] ASTM International, *Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester*, Annual Book of ASTM Standards, Standard ASTM D92-05, 2007.
- [171] World Trade Organization Technical Barriers to Trade Committee, *Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester 1*, ASTM International, Standard ASTM D93, 2020, p. 18.
- [172] R. Karthik and T. S. R. Raja, "Investigations of transformer oil characteristics," *IEEJ Trans. Electr. Electron. Eng.*, vol. 7, no. 4, pp. 369–374, Jul. 2012, doi: [10.1002/tee.21742](https://doi.org/10.1002/tee.21742).
- [173] M. Hirschler, Ed., *Electrical Insulating Materials: International Issues*. West Conshohocken, PA, USA: ASTM International, 2000, doi: [10.1520/STP1376-EB](https://doi.org/10.1520/STP1376-EB).
- [174] G. R. Gann, "Development of flammability criteria for transformer dielectric fluids," Centre Fire Res., Nat. Eng. Lab., Nat. Bur. Standards, U.S. Dept. Commerce, Washington, DC, USA, Tech. Rep. NBSIR 80-1992, Mar. 1992.
- [175] S. K. Subburaj, M. Rengaraj, and R. Mariappan, "Evaluating critical characteristics of vegetable oil as a biodegradable insulating oil for transformer," *Int. J. Emerg. Electric Power Syst.*, vol. 21, no. 5, pp. 1–9, Sep. 2020, doi: [10.1515/ijeeps-2020-0128](https://doi.org/10.1515/ijeeps-2020-0128).
- [176] O. J. Tola, A. M. Zungeru, F. O. Usifo, and A. J. Garba, "Experimental study of the characteristics of transformer oil and some selected vegetable oils," *Int. J. Eng. Res. Afr.*, vol. 23, pp. 13–23, Apr. 2016, doi: [10.4028/www.scientific.net/JERA.23.13](https://doi.org/10.4028/www.scientific.net/JERA.23.13).
- [177] K. G. Devi, M. Ravindran, and S. S. Kumar, "Analysis of critical parameters of vegetable oil as an alternate dielectric fluid to mineral oil," in *Proc. 10th Int. Conf. Intell. Syst. Control (ISCO)*, Jan. 2016, pp. 1–5, doi: [10.1109/ISCO.2016.7726885](https://doi.org/10.1109/ISCO.2016.7726885).
- [178] N. Pamuk, "Investigation of the usage of palm oils with the aim of insulation in high voltage power system equipments," *Tehnicki Vjesnik-Tech. Gazette*, vol. 22, no. 5, pp. 1–10, Oct. 2015, doi: [10.17559/TV-20141106141239](https://doi.org/10.17559/TV-20141106141239).
- [179] L. S. Mohammed, M. Bakruthen, M. Willjuice, and M. Karthik, "Studies on critical properties of vegetable oil based insulating fluids," in *Proc. Annu. IEEE India Conf. (INDICON)*, Dec. 2015, pp. 1–4.
- [180] S. Senthilkumar, A. Karthick, R. Madavan, A. A. M. Moshi, S. R. S. Bharathi, S. Saroja, and C. S. Dhanalakshmi, "Optimization of transformer oil blended with natural ester oils using taguchi-based grey relational analysis," *Fuel*, vol. 288, Mar. 2021, Art. no. 119629, doi: [10.1016/j.fuel.2020.119629](https://doi.org/10.1016/j.fuel.2020.119629).
- [181] R. Walvekar, D. A. Zairin, M. Khalid, N. M. Mubarak, and G. Tcsm, "Thermo-physical properties of naphthenic-palm oil methyl ester (POME) blended transformer oil," *J. Thermal Anal. Calorimetry*, vol. 147, no. 13, pp. 7193–7201, Jul. 2022, doi: [10.1007/s10973-021-11030-8](https://doi.org/10.1007/s10973-021-11030-8).
- [182] S. S. Kumar, M. W. Iruthayarajan, and M. Bakruthen, "Investigations on the suitability of Rice bran oil and corn oil as alternative insulating liquids for transformers," *IEEJ Trans. Electr. Electron. Eng.*, vol. 11, no. 1, pp. 10–14, Jan. 2016, doi: [10.1002/tee.22182](https://doi.org/10.1002/tee.22182).
- [183] H. M. Wilhelm, M. B. C. Stocco, L. Tulio, W. Uhren, and S. G. Batista, "Edible natural ester oils as potential insulating fluids," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 4, pp. 1395–1401, Aug. 2013, doi: [10.1109/TDEI.2013.6571461](https://doi.org/10.1109/TDEI.2013.6571461).
- [184] *Insulating Liquids—Measurement of Relative Permittivity, Dielectric Dissipation Factor (TAN δ) and DC Resistivity*, Standard IEC 60247, Feb. 2004, p. 53.
- [185] *Standard Test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids*, Standard ASTM D924-15, 2016, p. 8.
- [186] Transformers Committee IEEE, *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers*, IEEE Standard C57.147TM-2008, Jul. 2008.
- [187] GlobeCore. *Transformer Oil Relative Permittivity*. Accessed: Aug. 15, 2022. [Online]. Available: <https://globecore.com/oil-regeneration/transformer-oil-relative-permittivity/>
- [188] A. Sawada, "Space-charge polarization of a dilute electrolytic cell in the presence of diffuse double layers," *J. Appl. Phys.*, vol. 112, no. 4, Aug. 2012, Art. no. 044104, doi: [10.1063/1.4745046](https://doi.org/10.1063/1.4745046).



NUR S. SUHAIMI received the B.S. degree in electrical engineering major in power system from the University of Tun Hussein Onn Malaysia (UTHM), in 2014, and the M.S. and Ph.D. degrees in electrical and electronic engineering from the National Defense University of Malaysia (NDUM), in 2017 and 2021, respectively. From 2018 to 2021, she was a Research Assistant with NDUM, where she is currently a Postdoctoral Fellow. Her research interests include high voltage engineering, nanomaterial, dielectric material, and Raman spectroscopy.



MOHD T. ISHAK (Member, IEEE) received the B.Sc. degree in electrical engineering from the University of Tenaga Nasional, Malaysia, and the M.Sc. and Ph.D. degrees in electrical engineering from The University of Manchester, U.K. From 2013 to 2015, he was the Head of the High Voltage Laboratory, National Defense University of Malaysia and is currently a Professor with the Department of Engineering. His research interests include transformer condition monitoring, insulation ageing and diagnostic, asset management, alternative insulation materials for high voltage power equipment, and renewable energy.



ABDUL R. A. RAHMAN received the B.Eng. degree in electrical engineering and the M.Sc. degree in railway engineering from Universiti Tun Hussein Onn Malaysia. He is currently pursuing the Ph.D. degree with the National Defense University of Malaysia. His research interests include superconductor, semiconductor, magnetism material, advance material application, magnetocaloric effect, and X-ray diffraction.



MUHAMMAD F. MD. DIN received the B.Eng. degree in electrical and electronic and the M.Sc. degree in embedded system engineering from the University of Huddersfield, U.K., and the Ph.D. degree in superconductor from the University of Wollongong, Australia. He is currently a Lecturer and a Supervisor at the National Defense University of Malaysia. His research interests include superconductor, advance material application, renewable energy, magnetocaloric effect, X-ray diffraction, and neutron diffraction.



MOHD Z. Z. ABIDIN has studied from Royal Military College (RMC), in 1997. He received the Adv.Diploma degree in engineering (mechatronics) from the Box Hill Institute, TAFE, Australia, in 2001, and the bachelor's degree in electrical engineering from the University of Newcastle, Australia, in 2007. Started his career as a Mechanical and Electrical (M&E) Engineer at Henikwon Corporation Sdn Bhd, from 2002 to 2005 and from 2008 to 2011. He is responsible to prepare the design of busduct system for local and overseas projects, involved in project technical clarification and coordinated with consultants and contractors which related to busduct system, supervision and inspection at project sites and managed the progress of projects starting from starts until its completion and, part of a Trainer Engineer for overseas agents on how to design and coordination for busduct system. Since 2011, he has been continues his career at SGB Malaysia Sdn. Bhd. and currently as a Project Manager which responsible for project management activities and coordinating with various departments to meet customers expectation for company products; Power, Oil Distribution, and Cast Resin Transformers mainly for Oil and Gas EPCC projects under PETRONAS, EXXONMOBIL, DIALOG, TECHNIP, MRT, and LRT. He received his Project Management Professional (PMP) Certification, in 2018 and currently continues his ambition to be a certified Project Manager in the near future to come.



AZHAR K. KHAIRI received the B.Sc. degree (Hons.) major in physics from the National University of Malaysia (UKM), in 1993. Upon graduated, attending one year intensive Transformer Design Training at the Hitachi Design Center, Yokohama Works, Yokohama, Japan. He was worked at Hitachi, as a Flyback Transformer Designer, till 2005. He is currently working as a Transformer Designer at SGB MY, and the Head of the Department of Engineering. His expertise area in distribution transformers' electrical and mechanical. He has designing more than 2,000 transformers for customer in public, utility, oil, and gas segment. He is also the Head of Technical Support providing technical support and solution for customer especially in transformer retrofitting problems.

• • •