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Review

A state-of-the-art review on green nanofluids for transformer insulation

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ABSTRACT

The utilization of nanotechnology to enhance the properties of liquids has been underway for several decades. The systematic incorporation of nanoparticles into the base liquids has demonstrated its effectiveness in improving the thermoelectrical properties of insulating liquids. Vegetable-based liquids have emerged as potential alternatives to mineral-insulating oil due to the environmental concerns associated with the latter, despite their excellent electrical properties. Despite the environmental friendliness and health safety attributes of vegetable-based liquids, there are yet some limitations like low ionization resistance, high dielectric losses, low volume resistivity, and poor oxidation stability. These limitations are currently being addressed using different nanoparticles by the addition of an appropriate concentration to the base liquids. Though there is development in the synthesis of nanofluids using different nanoparticles for transformer insulation, no nanoparticle has been declared as one with ultimate performance. This review presents a comprehensive examination of recent findings in the literature concerning the use of nanofluids for transformer insulation, focusing specifically on the challenge of long-term stability. The review addresses various aspects including the characterization of nanoparticles, types of nanoparticles employed for enhancing insulating liquids, methods for preparing nanofluids, strategies for improving nanofluid stability, the impact of nanoparticles on vegetable-based insulating liquids, and the existing challenges associated with nanofluids. The report investigates these topics extensively, presenting a thorough analysis of the subject matter. It aims to provide valuable insights to researchers in this field and to encourage the exploration of sustainable and environmentally friendly insulating liquids suitable for green transformers.

1. Introduction

There is no doubt that the rapid increase in the world population has a proportionality with the high electricity demand. Transformers are part of the fundamental equipment used in power generation and distribution; this device helps in the easy transmission of electricity from the generation to the consumers at reduced losses. Taking into account factors such as insulation, load, operating temperature, and design, it is anticipated that a power transformer should have a lifespan of 32 years to 55 years [1]. However, without proper monitoring of the transformer's insulation system, the life expectancy of the device can decline significantly to less than 20 years [2]. The rapid deterioration in the transformer life is majorly caused by insulation failure. This is evident from the report made by the CIGRE (Council on Large Electric Systems) on transformers' reliability survey using 964 failures as seen in Fig. 1 [3].

The most used insulating oil at present for transformer insulation is a petroleum-based oil known as mineral insulating oil [4,5]. This insulating oil has excellent performance and has been serving the industry for decades. However, the negative environmental impact and fire safety concerns have called for alternative insulating liquids. Vegetable-based insulating liquids among others are now the prominent liquid suitable for the replacement of mineral insulating oils [6–8]. For example, the works published in [9–13] argue in favour of natural esters as an alternative to mineral oils. They have high biodegradability, high affinity for moisture, high fire point property, and non-toxicity [14–16].

Abbreviations: SDS, sodium dodecyl sulphate; PVP, polyvinylpyrrolidone; IEC, International Electrotechnical Commission; IEEE, Institute of Electrical and Electronics Engineers; CNTs, Carbon nanotubes; CTAB, Cetyltrimethylammonium Bromide; SDBS, Sodium Dodecyl Benzene Sulfonate.

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These aforementioned properties are important criteria for the selection of good insulating liquids. However, there are also some other important parameters like ionization resistance, dielectric loss, volume resistivity, and oxidation stability of the oil to consider. Unfortunately, vegetable-based insulating liquids have some drawbacks when considering those parameters [17].

The application of nanotechnology has shed light on improving the properties of insulating liquids by infusing the base oil with particles. Mineral insulating oil was previously infused with microparticles, however; the influence of these particles was detrimental to the dielectric properties of the base oil because of the instability of the microparticle in the oil. This instability was related to the high density of the microparticles which consequently deteriorates the dielectric properties of the base liquid [18,19]. The first application of nanoparticles on the base mineral oil was done by Segal et. al. [20] using magnetic Fe_3O_4 nanoparticles. An enhancement in the positive impulse breakdown voltage was observed and reported. In 2012, the influence of semiconductive nanoparticles on mineral oil (25# Karamay) was investigated in [21] and the semiconductive nanofluid prepared was observed to have ac, dc, and lightning impulse breakdown voltage up to 1.2 times compared to that of base oil. Dielectric properties of transformer oil-based silica nanofluids were reported by Rafiq et al. [22]. The nanofluids were prepared by dispersing silica nanoparticles into Kelamayi 25 mineral oil by sonication using two concentrations of 10 % and 20 % of silica nanoparticles. An improvement in the breakdown strength of nanofluids was observed with a pronounced improvement for 20 % of silica nanoparticles as compared to 10 % and pure oil [22]. Since the potential of nanoparticles on transformer insulating oil has been confirmed by several researchers [23–26], their application was further extended to natural esters to augment both thermal and electrical properties [27–31]. The dielectric properties of a commercial vegetable insulating liquid were enhanced in [32] using TiO_2, CuO, and ZnO nanoparticles. The dielectric strength and resistivity of the base liquid increased with the addition of the three nanoparticles, and a decrease in the dielectric loss was also observed. The properties of rapeseed oil in [33] were enhanced with TiO_2 nanoparticles coated with silica. The choice for selection of rapeseed oil may be attributed to the high percentage of monounsaturated fatty acid which has a relative balance between low temperature properties and stability to oxidation in transformer insulation. The dielectric loss of the base liquid decreases by an order and an increase in volume resistivity and breakdown voltage was observed from 1.09×10^{11} Ω·m to 7.42×10^{11} Ω·m and 60 kV/2.5 mm to 80.15 kV/2.5 mm respectively. Recent works on the enhancement of the dielectric strength of natural esters were also done in [34–38]. Consequently, these findings suggest a bright future for utilizing ester-based insulating nanofluids in transformers. Despite the extensive research published in the literature, a consensus has not been reached regarding the optimal type of nanoparticles, their size, and surface morphology for use in nanofluids. Diverse viewpoints and contradictory outcomes exist regarding these parameters. Therefore, there is a great need for further and proper investigation into the potential of nanofluids.

In this contribution, a detailed review of several nanoparticles used for the enhancement of physicochemical and dielectric properties of esters is done. The characterization methods of nanoparticles, preparation methods of nanofluid, and their effect on the base liquid are discussed. This is done to help research scholars both in academia and industries in the selection of suitable nanoparticles for enhancement of electrical insulating liquid.

2. Nanoparticles

Nanoparticles are classified as particles with dimensions less than 100 nm, and they have found several applications in the areas of medicine, agriculture, pharmaceutical, cosmetics, energy, sensor technology, optoelectronics, etc. [39–41]. In the past few years, several billions of dollars have been invested into nanotechnology by different countries like the USA, Japan, Korea, Germany, China, etc. due to the unique properties of nanoparticles [42,43]. Among the outstanding properties of nanoparticles is the high resistance to thermal and oxidation degradation, in addition to, a high surface area to volume ratio which gives it suitable attributes for enhancing the properties of dielectric insulating materials [44,45]. A simple diagrammatic illustration of the surface area to volume ratio can be seen in Fig. 2.

The synthesis of nanoparticles can be achieved in different ways viz., physical and chemical methods. The schematic diagram in Fig. 3 shows the different methods of synthesizing nanoparticles. In addition, recent research shows that nanoparticles can also be synthesized biologically using an extract from plants, microorganisms, and enzymes [46–49]. This is termed eco-friendly synthesis of nanoparticles; however, it requires serious attention, and it can be strenuous [50–55]. In the application of plants for the synthesis of nanoparticles, the extract from plants acts as the reducing agent in the reaction [41].

Characterizing nanoparticles is of utmost importance as they are

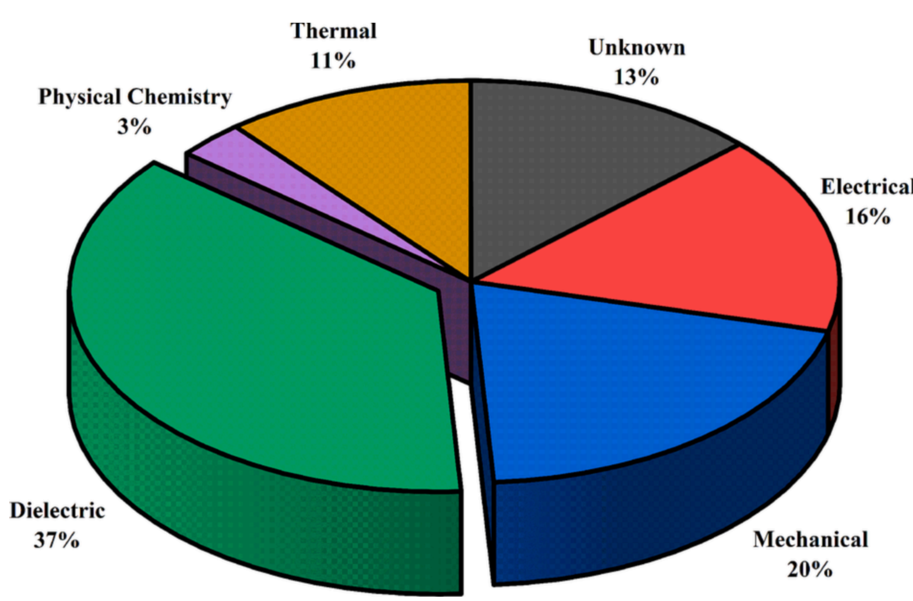

Fig. 1. Transformer Reliability Survey according to Council on Large Electric Systems.

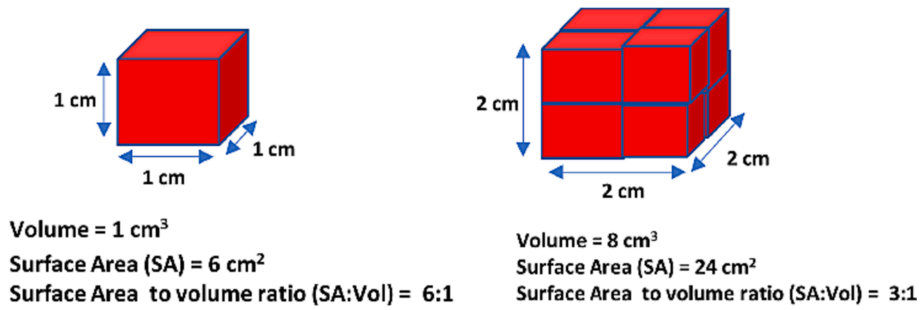

Fig. 2. Surface area to volume ratio.

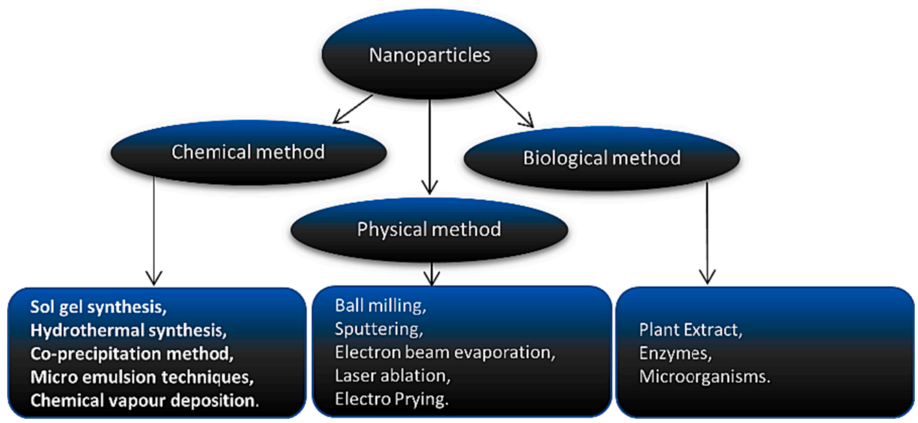

Fig. 3. Method of synthesizing nanoparticles.

produced through various chemical and mechanical methods and find applications in both academic and technological research. The term "characterization" refers to the overall process of examining the composition, structure, and other properties of a synthesized material. Through characterization, researchers gain insights into the fundamental characteristics of nanoparticles, allowing for a comprehensive understanding of their behavior, performance, and potential applications [40,56]. In addition, it also helps to understand the behavior of nanoparticles at molecular levels [57]. Due to advances in technology, there are several ways of characterizing nanoparticles and some of these methods are discussed in this section.

2.1. Characterization by FTIR

The synthesized nanoparticles can be characterized using spectroscopy techniques. Fourier transform infrared (FTIR) spectroscopy is a systematic method that can be used for the identification of material through functional groups. It can also be used for the determination of the quality and consistency of the synthesized sample. In this method, the principle of absorption and transmittance is used since all materials have their unique properties and no two different compounds produce the same infrared spectrum. In addition, the size of peaks in the spectrum is directly proportional to the percentage of material present [58]. Other available spectroscopy techniques such as ultraviolet–visible spectroscopy and Raman spectroscopy are also used.

2.2. Characterization by X-ray diffraction

The synthesized nanoparticles can be characterized using an X-ray-based technique. In the X-ray diffraction method, the principle of Bragg's law ($n\lambda = 2d\sin\theta$) is employed, where n, λ, d, θ are integer, X-ray wavelength, atomic plane spacing, and diffraction half angle respectively. The types and compositions of the synthesized sample can be determined by matching the peaks with standards like the International Centre for Diffraction Data (ICDD). XRD can also be used to determine the crystallinity of the particles through the sharp peaks in the spectrum [59]. The formula for calculating the nanoparticle crystallite size was developed in 1918 [60]. The crystallite size of the synthesized nanoparticles can be determined using the following Scherrer equation.

$$D = \frac{0.9 \times \lambda}{\beta \hat{A} \cdot cos\theta} \quad (1)$$

Where D is the crystallite size, λ is the wavelength in Angstrom, and β is the full width at half maximum of peaks in radian [61–63]. X-ray photoelectron spectroscopy is also good for the characterization of nanoparticles and it can be used for the elemental composition of the particle [64].

2.3. Characterization by SEM/TEM

Characterization based on microscopy technique: among the common equipment used for characterizing nanoparticles are Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM). The scanning electron microscope is used for the surface morphology of the nanoparticle while the transmission electron microscope is used to determine the internal structure of the nanoparticle. The surface morphology image in SEM is formed through the reflected electrons. However, for TEM, the internal structure image is formed through the transmitted electrons [65]. Some scanning electron microscopes are coupled with energy-dispersive X-rays; this is used to identify the elemental composition of the synthesized nanoparticles through the backscattered (primary) electrons [40].

2.4. Characterization by AFM

Atomic force microscopy (AFM) is a highly effective technique used to characterize synthesized nanoparticles, providing three-dimensional topographic images of the particles. This method offers several advantages, including minimal sample preparation, non-destructive analysis, and the ability to achieve atomic resolution imaging. AFM employs three different scanning modes: contact mode, noncontact mode, and tapping mode [66–69].

In contact mode, the AFM tip makes direct contact with the specimen, and the deflection of the cantilever is measured and used to generate the image. Noncontact mode, on the other hand, involves the AFM tip hovering above the specimen surface without making physical contact. The image is constructed based on the attractive forces between the sample and the tip.

Tapping mode, the third scanning mode, involves the oscillation of the cantilever through piezo motion. During the oscillation, the cantilever periodically touches the surface, causing a reduction in the oscillation amplitude. This reduction in oscillation amplitude is utilized to characterize the desired properties of the sample [70,71]. Additionally, AFM can be employed to assess surface roughness and visualize the surface texture of polymer nanocomposites.

2.5. Inductively coupled plasma mass spectrometry (ICP-MS)

This technique is a powerful method used for quantifying samples and characterizing their elemental composition. Its applicability extends to the field of nanotechnology as well [72,73]. This method utilizes a combination of inductively coupled plasma and mass spectrometry to determine the elemental composition and concentration of nanoparticles. By introducing the sample into a high-temperature plasma source, it undergoes atomization, ionization, and subsequent separation based on the mass-to-charge ratio within the mass spectrometer [74–76]. This analytical technique offers high sensitivity and the capability to analyze multiple elements simultaneously, making it an efficient approach for nanoparticle analysis. Moreover, it can provide valuable information regarding the purity of the nanoparticles [76].

Nanoparticles can be classified based on their different band gaps and metallic properties. In Table 1, nanoparticles are classified as metallic and non-metallic. In Table 2, oxides of nanoparticles are also classified based on their energy gap (conductive, semiconductive, and insulative).

3. Nanofluid preparation, stability enhancement, and stability evaluation

In this section, the methods of preparing nanofluid are discussed, the ways of improving the stability of nanofluid are discussed, and how the stability of nanofluid can be evaluated is also emphasized.

3.1. Nanofluid preparation and stability enhancement

The term **nanofluid** is a composite liquid containing two different phases which are the solid and liquid phases. The fluid is engineered to enhance both the thermophysical and electrical properties of the base fluid [81]. The unique properties of the particles at the nanoscale have brought several advancements in science and engineering because of their large surface area-to-volume ratio (Fig. 2). In the years 2018, 2019, and 2020, the field of nanofluid research garnered significant interest, resulting in the publication of a substantial number of research papers. Specifically, there were over 2,642, 3,707, and 4,200 research papers respectively focused on nanofluids during those years [82], which shows an exponential increase in the field of nanofluids. The preparation of nanofluids is done in two different ways, the one-step method and the two-step method [83]. These two methods have different advantages, the stability of the composite fluid prepared by one step method is higher than the stability of the composite fluid prepared by the two-step method. However, in terms of their production cost, the one-step method is highly expensive to achieve but the two-step method is cost-friendly. In addition, precise estimation of the direct effect of nanoparticles on the base fluid using the one-step method is not guaranteed since there could be some remnant of reactants in the base fluid due to incomplete reaction [84].

Table 1
Classification of nanoparticles into metallic and non-metallic [2,77].

Metallic nanoparticles	Non-metallic nanoparticles
Au and Ag nanoparticles	Silica (SiO_2)
Cu	Titania (TiO_2)
Au	Alumina (Al_2O_3)
Si	Zinc Oxide (ZnO)
Fe	Copper Oxide (CuO)
Al	Iron Oxide (Fe_3O_4)
–	Aluminum nitride (AIN)
–	Carbon nanotubes (CNTs)

Table 2
Classification of oxides of nanoparticles based on energy gap [78–80].

Conductive nanoparticle	Semi-conductive nanoparticle	Insulating nanoparticle
Fe_3O_4	TiO_2	SiO_2
ZnO	WO_3	Al_2O_3
SiC	CuO	AlN
Fe_2O_3	Cu_2O	BN
	ZrO_2CdS	$BaTiO_3$
		SiN_4

The one-step method eliminates several stages typically involved in nanofluid synthesis, including transportation, drying, storage, and mixing of nanoparticles. The nanofluid is prepared simultaneously by adding two different reactants as seen in Fig. 4 and it gives the nanofluid long-term stability [84–87]. However, in the two-step method as seen in Fig. 5, the nanoparticles are synthesized separately either by chemical, physical, or biological methods, then mixed directly with the base fluid. In some cases, **steric stabilization** is applied to enhance the stability of the particles in the base fluid. This is done by the addition of surfactants to the base fluid to enhance the stability of nanoparticles. Since the nanoparticles are non-lipophilic, it is difficult for them to attach to the base fluid, the surfactant which is also called dispersant is used to create a continuity between the nanoparticle and the base liquid [84]. It also reduces the surface tension of the base fluid and allows easy immersion of the nanoparticle. The surfactant has a hydrophilic head and hydrophobic tail [84]. However, when the transformer is highly energized and the temperature is increased, there is a tendency for the nanofluid to lose its stability and efficiency. This is because, at high temperature operation, there is a probability of bond breaking which consequently leads to sedimentation of the nanoparticles [84,88–90]. The stability in the two-step method is also enhanced through surface modification of nanoparticles which is also known as **electrostatic stabilization**, this is done without adding a surfactant to the base fluid but chemically adsorbing

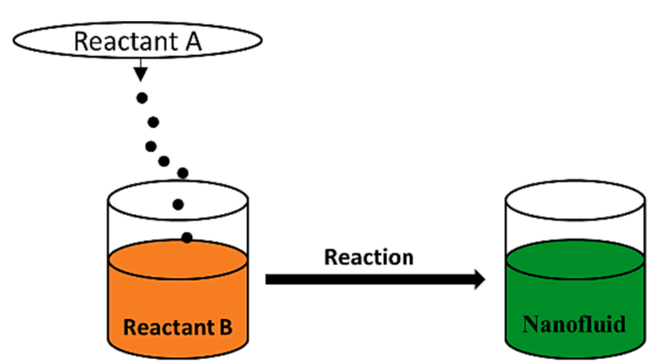

Fig. 4. One-step method of preparing nanofluid.

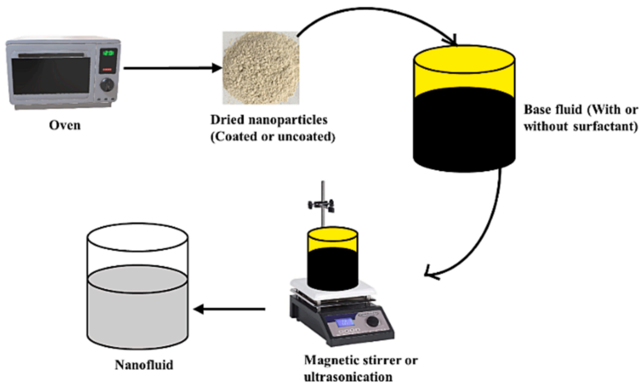

Fig. 5. Two-step method of nanofluid preparation.

the coating materials on the surface of the nanoparticles before mixing the nanoparticles with the base [78,91]. This is preferable because it is a means of eliminating the effect of other chemical compounds (surfactants) on the base fluid. Table 3 shows some of the surfactants and coating materials that have been successfully employed in the literature.

Other surfactants used for general nanofluid preparation are Dodecyl trimethylammonium bromide (DTAB), and Hexadecyl trimethyl ammonium bromide (HCTAB) [107,108]. In addition, there are other methods of improving the stability of nanofluids including *pH* modification. However, the addition of surfactants has been the choice of researchers due to their cost-friendliness and simplicity. Lastly, the combination of electrostatic and steric stabilization is also adopted for the nanofluids preparation. This stabilization technique is known as **electrosteric stabilization** [80].

3.2. Stability evaluation

The stability of the prepared nanofluid can be assessed in several ways. In some of the research works the stability of nanofluids was observed through physical observation. For example, the study made in [36] observed the stability of prepared nanofluids through visual inspection and it was reported that the oil was stable even after 24 h. Dynamic light scattering and morphological analysis using scanning electron microscopy are also systematic ways of analyzing the stability of nanofluids. These methods were also used in [36] to analyze the stability of the prepared nanofluids. The SEM micrograph shown in Fig. 6 indicates a minor agglomeration within the nanofluid. However, this observation is indicative of an evenly distributed nanoparticle distribution, leading to a stable nanofluid.

The stability of nanofluids can also be determined by **Zeta potential measurement**. This is done by measuring the potential difference that exists between the diffuse layer and the stern layer as seen in Fig. 8. The value of zeta potential is in mV and it is directly proportional to the electrophoretic mobility [109]. The zeta potential can be calculated from Henry's equation given in Eq. (2) and it can be negative or positive in magnitude depending on the basicity and acidity of the solution respectively [110–112]. It is important to notice that at the *pH* point where zeta potential becomes zero, there is a high tendency for agglomeration of nanoparticles. This point is known as the isoelectric point [113]. This is an indication that *pH* value is among the important parameters that determine the stability of nanofluids. Among other parameters that also affect the stability of nanofluids are the concentration of the particles and the ionic strength.

$$U_E = \frac{2\varepsilon\zeta}{3\eta} f(\kappa a) \tag{2}$$

U_E is the electrophoretic mobility, ε is the dielectric constant, ζ is zeta potential, η is viscosity, and $f(\kappa a)$ is called Henry's function [115].

In a situation where the EDL (Electric double layer) is very small relative to the radius of the particle, the value of Henry's function $f(\kappa a)$ is 1.5 which reduces Eq. (2) to Eq. (3) called Helmholtz-Smoluchowski equation. On the other hand, when the EDL is bigger compared to the particle size, the $f(\kappa a)$ is 1 and Eq. (2) reduces to Eq. (4) which is known as the Huckel equation [116].

$$U_E = \frac{\varepsilon\zeta}{\eta} \tag{3}$$

$$U_E = \frac{2\varepsilon\zeta}{3\eta} \tag{4}$$

The zeta potential value determines whether the particles in the base fluid are stable or not. Table 4 shows different stages of stability in nanofluid preparation. For a nanofluid to be considered a stable fluid, the zeta potential must be, or greater than ±30 mV [117]. The application of a UV–Vis spectrophotometer can also be used to determine the stability of nanofluids. The maximum absorbance of the freshly prepared nanofluid is measured, and the sample is kept for some specific time to observe the sedimentation rate. After the set time elapses, the

Table 3
Surfactants and coating materials for the stability of transformer nanofluids.

Nanoparticles	Surfactant/ Surface Coating	Material	Reference
Al_2O_3	Surface Coating	Oleic acid	[36,37,92–94]
Al_2O_3	Surfactant	SDBS	[77,95]
Al_2O_3	Surfactant	SDS	[96]
Al_2O_3	Surfactant	Oleic acid	[79]
Al_2O_3	Surfactant	PVP	[96]
SiO_2	Surfactant	CTAB	[97]
SiO_2	Surfactant	Oleic acid	[97]
SiO_2	Surfactant	Span-80	[97]
GOZnO	SurfactantSurfactant	Oleic acidCTAB	[2998]
TiO_2	Surfactant	CTAB	[77,98]
TiO_2	Surfactant	Oleic acid	[29]
TiO_2	Surface coating	SDS	[99]
TiO_2	Surface coating	CTAB	[99]
TiO_2	Surface coating	Oleic acid	[35–37,92,100,101]
TiO_2	Surface coating	Silicon oil/ steric acid	[102]
WO_3	Surface coating	Oleic acid	[61]
Fe_3O_4	Surface coating	Oleic acid	[91,103]
Fe_2O_3	Surface coating	Oleic acid	[36,104]
Fe_2O_3	Surface coating	Oleate coated	[104]
Fe_2O_3	Surfactant	Oleic acid	[105]
AlN	Surface coating	Oleic acid	[106]
AlN	Surfactant	Oleic acid	[94]

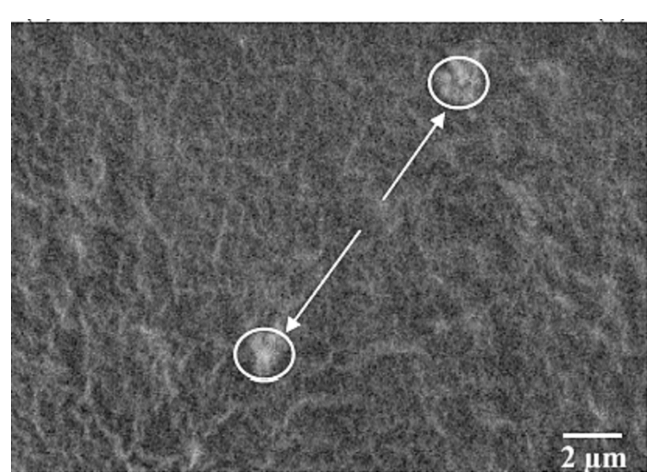

Fig. 6. The SEM micrograph of nanofluid with arrows pointing to the agglomerated nanoparticles [36].

Table 4
Nanoparticle zeta potential range [40,127,128].

Particles characteristics	Range in mV
Aggregation of nanoparticle	0–5
Slight stability	5–20
Average stability	20–40
Extreme stability	> 40

absorbance test is done on the same sample to see if there is a change in the absorbance value. The smaller the difference, the more stable the sample is, and vice versa (Fig. 7). The same principle applies to turbidity tests. The work reported in [79] analyzed the effect of Al_2O_3 nanoparticles on the properties of natural ester obtained from soybean and mineral oil. The size of the particles used for the analyses was 60 nm and good stability of nanofluid was reportedly obtained at 0.02 wt% loading using a UV–Vis spectrophotometer. The reduction in absorbance was used to justify the stability of the particles in the oil. The stability test was also confirmed using Nephelometric turbidity unit, the sample with the least reduction in NTU was reported to be the most stable sample among others. In addition, the other methods for determining the stability of nanofluids are the sedimentation method, centrifugation method, and spectral analysis method [85,118–126].

The Derjaguin, Landau, Verwey, and Overbeek (DLVO) theory has been used to analyze the stability of nanofluids. This theory utilized the Vander Waals attractive force and electrostatic repulsive force. This is represented by Eq. (5) where f_n is the net force, f_r is the repulsive force and f_a is the attractive force [129,130].

$$f_n = f_r - f_a \tag{5}$$

Fig. 9 shows the schematic diagram which describes DLVO theory. From Eq. (5), if $f_a < f_r$, the net force is repulsive and the nanofluid is stable. From Fig. 9, point b is the maximum point corresponding to the point dominated with repulsive force, at this point no sign of agglomeration and there is maximum stability. At point d, the repulsive force is low and there is a probability of the particle settling down without agglomeration. In the same vein, if$f_a > f_r$at points a and c, there exists an attractive force that leads to the agglomeration of particles and consequently causes sedimentation. Point a is called the primary minimum which has deep potential, if particles coagulate, they form hard cakes (flocculation). At point c, the potential is shallow, and the agglomerated particles can be separated by simple mechanical stirring.

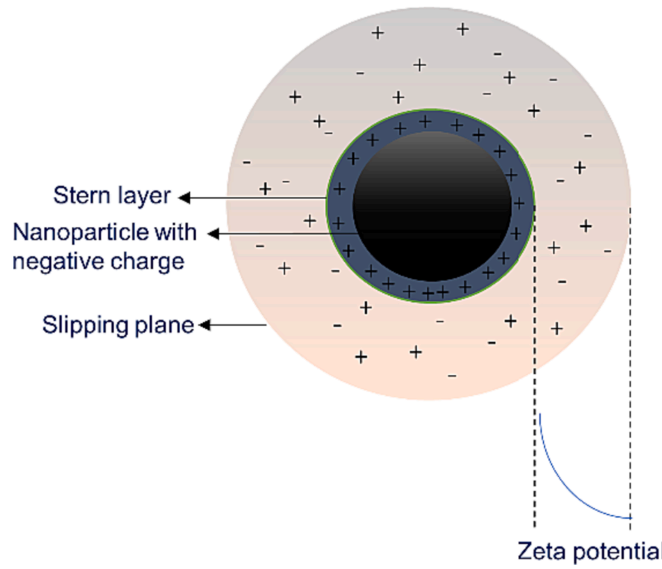

Fig. 8. Zeta potential of solid–liquid phase.

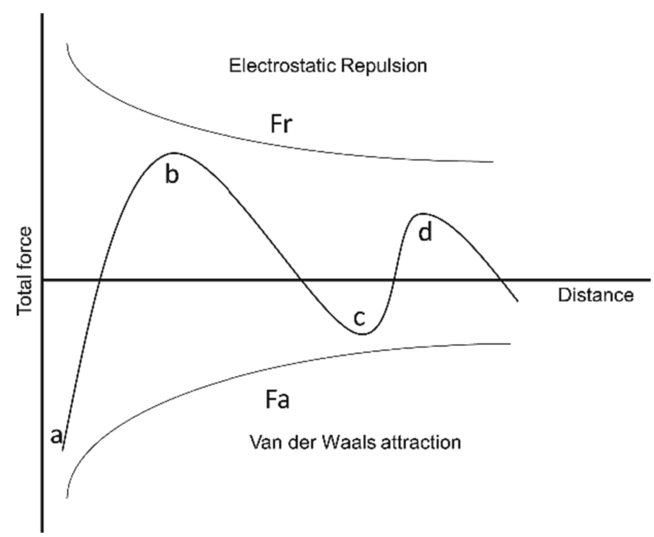

Fig. 9. DLVO Theory.

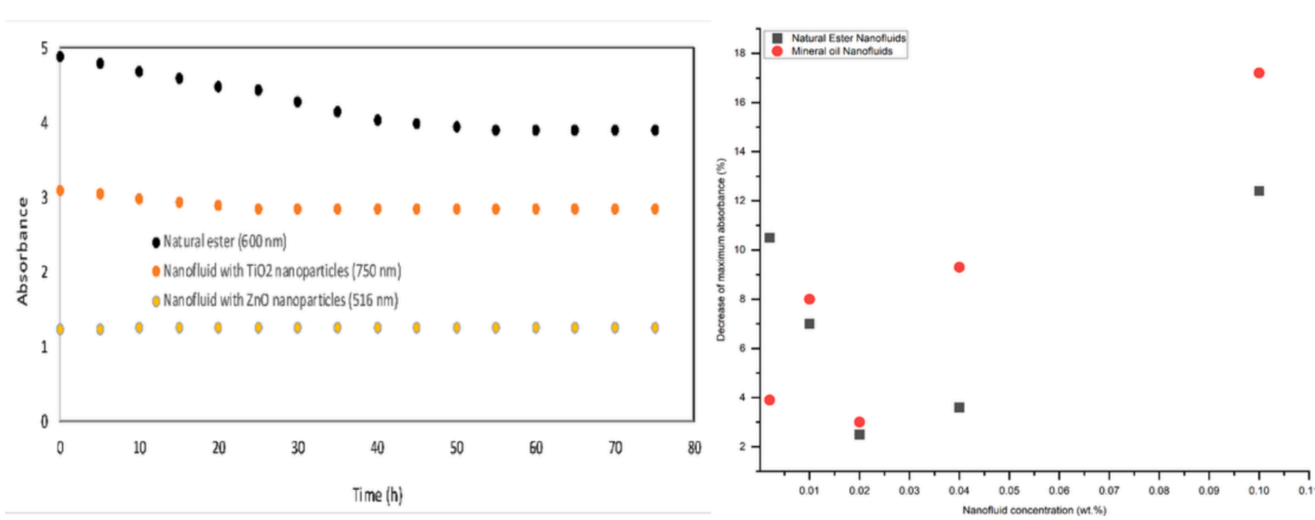

Fig. 7. Stability assessment of prepared nanofluids using UV–Vis spectrophotometer [79,114].

4. Effect of some selected nanoparticles on the physicochemical properties of natural esters

This chapter focuses on examining the impact of nanoparticles on improving the physicochemical and dielectric properties of natural esters. Specifically, it discusses the physical and chemical characteristics of nanofluids created using various types of nanoparticles.

4.1. Physical properties

4.1.1. Viscosity

One of the important parameters to be considered when selecting liquid insulating material for transformer insulation is viscosity. This measures the friction that exists between the layers of the fluid and directly influences the flow of the fluid. The two types of viscosity are dynamic which measures the force needed to make the fluid flow and kinematic viscosity which measures the rate at which fluids flow. The former is good for measuring the viscosity of non-newtonian liquids while the latter is good for determining the viscosity of Newtonian fluids like oil. In addition, the basic difference between the two types of viscosity is the density of the material and they are related by Eq. (6). V is the kinematic viscosity, ρ is the density and η is the dynamic viscosity of the liquid [131].

$$V \times \rho = \eta \tag{6}$$

The common standard for determining the viscosity of an insulating liquid is ASTM D445 [132,133]. The viscosity of insulating oil depends on the temperature and this decreases when the temperature increases and vice versa. When the temperature of the liquid increases, the viscosity of the liquid decreases due to a reduction in the intermolecular forces that exist between the molecules of the oil. A good insulating liquid, especially the transformer insulating liquid should have a low viscosity [134]. This has been theoretically proven by the relationship between the heat transfer coefficient and the dynamic viscosity shown in Eq. (7) [8].

$$h = C \times \left(\frac{\Delta T_{oil}}{\mu(T)}\right)^n \tag{7}$$

In this equation, h is the heat transfer coefficient, μ is the dynamic viscosity, T is the temperature in kelvin, ΔT_{oil} is the oil temperature difference, n is a constant that depends on the oil circulation, and C is a parameter that depends on the density, thermal conductivity, thermal expansion coefficient, and specific heat of the oil [8]. The utilization of a low-viscosity liquid in transformer insulation facilitates rapid heat dissipation and helps prevent the formation of hot spots. The incorporation of nanoparticles has emerged as a recent approach for enhancing natural ester-insulating liquids. However, it is important to investigate the impact of nanoparticles on the modified base liquid, particularly in terms of its cooling characteristics. Numerous studies have been conducted, and a summary of the progress reported in the literature, including the viscosity of natural ester-based nanofluids can be found in Table 5. This section provides an overview of the effects of various types of nanoparticles on the base liquid, as reported by different authors.

TiO_2 nanoparticle

The assessment done on the thermophysical properties of natural esters and synthetic ester was reported in [29]. The size of the used TiO_2 nanoparticle was 80 nm–110 nm. The viscosity of base oil and the nanofluids was reportedly measured using a redwood viscometer apparatus in line with ASTM D445. An increase in the viscosity of the base liquid after the first loading (0.01 wt%) was reported which was attributed to the clustering of the nanoparticles with the oil thereby increasing the friction existing between the layers. The continuous loading of nanoparticles decreases the viscosity which was attributed to the self-lubricating behavior of the nanoparticles. The effect of TiO_2 nanoparticles was studied on methyl ester from palm kernel oil in reference [92] and there was an observed increase in the viscosity of the base liquid. Specifically, when comparing the base liquid to a nanofluid containing 1 wt% nanoparticles, a percentage difference of 16 % was reported. The viscosity of methyl ester nanofluid obtained from transesterification of Soybeans and Palm ester using Brookfield DV-E viscometer in accordance with ASTM D2196 is reported in [98]. The temperature was varied from 27 °C to 70 °C and the spindle was made to rotate at 100 rpm. There was no specific difference in the viscosity of the base oil even after the loading of TiO_2 and ZnO nanoparticles. It was reported that the viscosity of the synthesized nanofluid is lower than the viscosity of mineral oil which makes the nanofluids a promising cooling liquid.

Graphene oxide (GO) nanoparticle

In [29], an interesting property of nanofluid synthesized using graphene oxide nanoparticles was reported. The viscosity of the graphene oxide nanofluid at room temperature was reported to be greater than the viscosity of the base liquid, however, when the temperature increases to 40 °C at higher loadings of nanoparticles, 0.03 wt% and 0.05 wt%, the viscosity of the nanofluids was observed to be lower relative to that of base liquid (natural ester) at the same test temperature.

Al_2O_3 Nanoparticle

In [79], the preparation of nanofluid was accomplished using a modified two-step method that involved the addition of a dispersant (Ethanol) following the mixing of the nanoparticle and surfactant (Oleic acid). This dispersant allowed easy penetration of particles in-between the molecules of the oil which consequently enhanced the stable suspension of nanoparticles. The viscosity of the oil was measured in

Table 5
Summary of the effect of nanoparticles on the viscosity of vegetable-based liquids.

Author	Nanoparticles	Size of nanoparticles	Remarks	Reference
Khan et al.	Graphene Oxide & TiO_2	100 nm–120 nm, 80 nm–110 nm	The addition of nanoparticles increases the viscosity of the base liquid.	[29]
Oparanti et al.	TiO_2, Al_2O_3	11 nm, 18 nm	A slight increase in the viscosity of the base liquid was observed.	[92]
W. Saenkhumwong and A. Suksr	TiO_2, ZnO	21 nm, <100 nm	No significant difference in the viscosity of the base liquid and the nanofluids	[98]
Olmo et al.	TiO_2	10 nm–20 nm	The loading of nanoparticles affects the viscosity of the base oil	[135]
Jacob, J., et al.	Al_2O_3	60 nm	The effect of nanoparticles loading on the base liquid is considered negligible.	[79]
Mohamad et al.	Fe_3O_4, TiO_2, Al2O3	15 nm −20 nm	No significant effect of the nanoparticles on the base liquid	[136]
Madavan et al.	Al_2O_3, BN, Fe_3O_4	30 nm–70 nm, 40 nm, 50 nm–75 nm	An increase in the viscosity of the base liquids was observed at every loading of the nanoparticles.	[137]
Oparanti et al.	SiO_2	18 nm	No significant effect of nanoparticles on the viscosity of the base liquid.	[61]
Fernández et al.	TiO_2, ZnO	45 nm, 60 nm	An Increase in the viscosity of the base oil was observed for both nanoparticles at 20 °C	[114]
Ghislain et al	FeO_3	100 nm–250 nm	The viscosity of the base liquid increases with increasing nanoparticle concentration.	[138]
Madavan and Balaraman	Fe_3O_4, ZnO, SiO_2	50 nm–80 nm	The viscosity increases with nanoparticle loading.	[139]

accordance with the ASTM standard D445. The results indicate that the loading of nanoparticles at 0.002 wt%, 0.01 wt%, 0.02 wt%, 0.04 wt%, and 0.1 wt% did not significantly affect the viscosity of the base liquid. In accordance with these findings, the comparison between the sample containing the highest nanoparticle loading and the base oil revealed a 14.3 % increase in viscosity. This increase can be considered negligible or relatively small in magnitude. However, the viscosity of the base liquid and synthesized nanofluid is almost 4 times the viscosity of mineral oil which may be a big disadvantage when considering this fluid as an insulating oil. In contrast to the report in [79], a decrease in the viscosity of the base methyl ester from palm kernel oil was reported by [92] after the addition of 0.2 wt% Al_2O_3 nanoparticles to the base liquid. In addition, the continuous loading of nanoparticles from 0.4 wt% to 1 wt% shows no significant effect on the base liquid. This in their report was attributed to hydrophobic and or, reducing properties of Al_3 [92]. The viscosity of palm fatty acid esters and their nanofluids was studied using different nanoparticles in reference [136]. According to the report, the addition of nanoparticles to the base oil did not significantly impact its viscosity. At a temperature of 40 °C, it was determined that the percentage difference in viscosity between the base oil and the nanofluids was less than 0.5 %. The effect of Al_2O_3, boron nitrate (BN), and Fe_3O_4 nanoparticles was studied on Honge oil, Neem oil, mustard oil, and punna oil [137], the loading of nanoparticles into the base oil shows a significant enhancement on the viscosity of the base oil, however, the viscosity decreases as the temperature increases.

SiO_2 Nanoparticles

The dynamic viscosity of neem oil methyl ester nanofluid prepared using SiO_2 nanoparticles of average particle size 18 nm was measured by [61], the report shows that there is an insignificant effect on the viscosity of the base liquid. Various other types of nanoparticles utilized to improve the performance of natural esters are ZnO and WO_3.

4.1.2. Flash point

In high voltage engineering, the flash point of the insulating oil used in the equipment is highly important due to its critical role in ensuring the safety and well-being of workers, as well as the security and longevity of the equipment itself. The temperature at which there is an ignition due to flame generated as a result of blistering activities at the liquid surface is known as flash point [140]. According to NEC^{TM}, the flash point of a liquid should be greater than 300 °C before it can be classified under a less flammable liquid [140,141]. The flash point of an insulating liquid can be negatively affected by the presence of impurities in the oil. Natural esters have a flash point greater than mineral oils and it is classified under the K class according to IEC 61100 [142]. When high voltage equipment is at its optimum performance perhaps overloaded, the temperature of the insulating liquid increases. At a very high temperature, if the flash point of an insulating liquid is low, it may lead to a fire outbreak in the transformer. Also, in the case of failure when the dielectric materials cannot withstand the stress generated by a secondary short circuit, lightning, switching impulse, ferroresonance, etc., the arc decomposes some portions of the liquid thereby creating some gases in the tank of the transformer. If the arc is sustained for a short while, more gases are generated leading to high pressure in the tank. The volatile gases find their way out through the weakest link and ignite. In the case of mineral oil with a low fire point, the probability of transformer explosion is high, however, due to the high fire point of natural esters, they are capable of quenching the fire and avoiding a fire outbreak [143]. To date, there have been no reported instances of fire outbreaks involving transformers that run on natural esters. Table 6 highlights the flash point classification of insulating oil based on various standards. Numerous studies have reported the flash point of mineral oil nanofluids and natural esters nanofluids, all of which have shown promising results.

Table 6
The flash point (°C) of insulating oil according to standards [140].

Insulating oil	ASTM	IEC	IEEE	Category
Mineral Oil	≥145	≥135	–	O1
Natural Ester	>275	≥250	≥275	K2

The flash point of different vegetable-based nanofluids, Honge oil, Neem oil, mustard oil, and Punna oil was studied in ref. [137]. The natural esters were doped with Al_20_3, BN, and Fe_3O_4 and the flash point was measured in accordance with ASTM D92 using a closed-cup Pensky Martin kit. The report shows a positive enhancement in the flash point of all the base liquids including the transformer oil. An investigative study done by [35] on the effect of TiO_2 nanoparticles on Jatropha, Neem, and the composite of Neem and Jatropha shows a positive enhancement after loading the nanoparticle into the base oil with concentration varying from 0.2 wt% to 1 wt% at a step of 0.2. The flash point of palm kernel oil methyl ester doped with both TiO_2 and Al_2O_3 nanoparticles was measured in ref. [92] in accordance with ASTM D93. The loading of nanoparticles into the methyl ester increases the flash point of the base liquid by 11 % and 9 % for TiO_2 and Al_2O_3 nanoparticles respectively. The methyl ester from neem oil was doped with WO_3 and SiO_2 nanoparticles in reference [61]. The flash point was measured, and the report indicates that the addition of nanoparticles, specifically WO_3 and SiO_2 nanoparticles, resulted in respective improvements of 8.57 % and 5.76 % in the flash point. The effect of Alumina was investigated on the ester from Soybean by Jacob et al. according to ASTM D92 [79]. The flash point increases as the concentration of nanoparticles in the base liquid increases. The flash point of nanofluids prepared from soybean esters and palm ester using ZnO and TiO_2 nanoparticles was studied in [98] using a closed cup flash tester, and an enhancement in the flash point of both base liquids using the two nanoparticles was reported. In [139], Fe_3O_4, ZnO, and SiO_2 nanoparticles were utilized to improve the thermal properties of sunflower oil and rapeseed oil, resulting in an increase in their flash points by more than 6 %. In [144], more than 10 % enhancement in the flash point of punga oil was reported after the addition of 0.01 wt% ZnO nanoparticles. The addition of silica nanoparticles to corn oil and coconut oil in [145] shows no pronounced effect on the properties of the base oil.

It is noteworthy that all studies on the impact of nanoparticles on the flash points of natural esters have reported a positive effect. This may be due to the presence of nanoparticles in the base liquid, which hinders the easy dissociation of oil molecules when exposed to high temperatures.

4.1.3. Pour point

The pour point of insulating oil is an important parameter that determines the fluid flow especially, under low-temperature conditions. Mineral oil used in transformer insulation has a good pour point with an excellent performance at sub-zero regions. Generally, natural esters have higher pour points relative to mineral oil, but synthetic ester has a pour point temperature somewhat close to that of mineral oil. Several approaches have been used to reduce the pour point temperature of vegetable-based insulating oils through chemical modifications and the addition of depressants [8]. It is important to make a critical observation of how nanoparticles impact the pour point of natural esters to determine whether they exert a positive or negative influence on it. The addition of nanoparticles to the base liquids can prevent oil molecules from crystalizing and this might be the reason for the result obtained in [92] where a decrease in the pour point of palm kernel oil methyl ester after the addition of Al_2O_3 nanoparticles was reported. However, in the same work, the addition of TiO_2 nanoparticles makes the pour point of the same base liquid increase slightly. The different effects observed by loading different particles into the same base liquid could be a result of nanoparticle properties. The pour point property of mineral oil nanofluid and pongamia oil methyl ester nanofluid prepared using exfoliated hexagonal boron nitride was studied in [146]. The addition of nanoparticles to base liquid decreases the pour point of the base oil and this was attributed to the presence of nano-dimensional particles in the oil which prevents easy wax crystallization of the oil molecules. The effect of ZnO nanoparticles on coconut oil was observed in [147] at the optimum loading of the nanoparticles. The pour point of the base liquid decreased from −12 °C to −13 °C. Due to the varying properties of nanoparticles, further investigation into their effect on the base oil pour point temperature is needed. Thermal properties and nanoparticle size are among the properties of nanoparticles that could potentially impact the pour point of base liquids.

4.2. Chemical properties

4.2.1. Acid value

The acid number is a significant indicator that provides information about the grade or excellence of insulating oil. To prevent the dissociation of H^+ ions from the acid in insulating oil, which, when combined with water, produces hydronium ions and raises the hydronium concentration in the solution, resulting in increased conductivity, it is crucial to minimize the total acid number of the oil. In addition, a high concentration of acid content accelerates the degradation of insulating materials and the corrosion of metal components within the transformer [148]. The American Society for Testing and Materials specifies that the acid value of insulating oil in use should not exceed 0.2 mg KOH/g [149]. The acid value can be determined using Eq. (8) [150].

$$TAN = \frac{(E_p - B_v)N_{KOH}M}{W} \quad (8)$$

where TAN is the total acid number, mgKOH/g, E_p is the equivalent point, ml, B_v is the blind value, ml, N_{KOH} is the normality of the titer (KOH), M is the molar mass of the titer, and W is the weight of the oil sample, g [151,152]. It has been observed that natural esters tend to have a higher acid value compared to mineral oil, and this difference may be attributed to the types of fatty acids present in the oil. IEC has set the maximum acid value for natural ester at 0.6 mgKOH/g, as natural ester's acidity can increase quickly due to its poor oxidation stability. Inadequate monitoring of the oil's acidity could lead to a rise in temperature due to conduction loss, potentially affecting the transformer's performance and leading to the degradation of both liquid and solid insulators within the transformer.

The addition of nanoparticles to the base liquid could influence the acidity depending on the nature of the nanoparticles and the type of coating on the surface of the nanoparticles. In order to ascertain the appropriateness of nanofluids for insulation in transformers, it is vital to examine their acid properties thoroughly. Careful characterization of these properties can enable researchers to identify the most appropriate materials for this application, thereby enhancing the safety and reliability of transformer systems. Different nanoparticles have diverse effects on the base liquids because of their *pH* values. The acidity of nanofluids can vary based on the characteristics of the nanoparticles used during their preparation.

FeO_3 nanoparticles were used in [34] to prepare a nanofluid using palm kernel oil methyl ester as the base liquid. The effect of loading nanoparticles into the base liquid was studied on acidity by varying the percentage concentration of nanoparticles from 0.10 wt%, 0.15 wt%, and 0.20 wt%. It was observed that the loading of nanoparticles into the base oil increases the acidity of the oil with a high increase when 0.10 wt % loading was added. In [79], the presence of Alumina nanoparticles had an impact on Soybeans. Specifically, the study found that there was a direct correlation between the loading of nanoparticles and acidity.

The accelerated thermal aging of natural ester and natural ester nanofluid prepared using TiO_2 and ZnO nanoparticles was also studied in [114]. The nanofluids from the study showed a higher percentage increase in acidity compared to the base liquid, indicating that the presence of nanoparticles promoted the formation of acidic by-products in the oil. In essence, the incorporation of nanoparticles into the base oil can significantly impact the acid number of the base liquid. Therefore, it is important to carefully select nanoparticles that are suitable for the base oil to ensure that they do not have an adverse effect on the properties of the oil, particularly its acid number.

4.2.2. Oxidative stability

Oxidative stability refers to the ability of an oil or fluid to resist and withstand the detrimental effects of oxidation over time. The stability of natural esters to oxidation when used in power equipment, especially in power and distribution transformers is very important and cannot be undermined. When the insulating oil utilized in high-voltage equipment undergoes oxidation, the resulting oxidation byproducts have an impact on both the cooling and insulating properties of the oil. This, in turn, can lead to an expedited degradation process and diminished operational reliability. For example, when the natural ester oil gets oxidized, the oil viscosity increases which leads to poor cooling of the transformer. Also, the chemical properties of the oil change which consequently increases some factors like ketones, aldehydes, etc. [153]. Extensive research and analysis have revealed that the oxidative stability of natural ester is a matter of significant concern [154]. When compared to mineral oil, natural ester exhibits inferior oxidative stability properties [83,140]. Natural esters are made of fatty acids which are classified into saturated, monounsaturated, and polyunsaturated [155,156]. The degree of saturation in fatty acids has a linear relationship with its oxidative stability. In other words, the higher the degree of unsaturation, the higher the instability of the oil to thermo-oxidation. Examples of oils with high percentages of saturated fatty acid are palm kernel, coconut oil, etc. Those with a high percentage of unsaturation are canola oil, jatropha oil, soybean oil, etc. [157–159]. Few reports exist in the literature about the oxidative stability of nanofluid prepared from natural ester and the reports show a reasonable degree of enhancement in the oxidative stability of natural esters. In [160] it was shown that the utilization of eggshell-synthesized nanoparticles resulted in the enhancement of rice bran oil. The addition of 0.25 wt% and 0.5 wt% eggshell nanoparticles led to an increase in the thermos-oxidative stability of the base liquid. The reported percentage improvements were 18.2 % and 25 % respectively.

When nanoparticles are introduced into natural esters, their small size allows them to effectively interact with the oil molecules. These nanoparticles can attach themselves to the oil molecules, forming a protective layer around them. This attachment helps to shield the oil molecules from external factors, such as oxygen, heat, and light, which can trigger oxidation reactions [161]. By preventing easy access of these external factors to the oil molecules, the nanoparticles effectively increase the oxidation stability of the oil. Additionally, the nanoparticles themselves may possess antioxidant properties, which can further contribute to the enhanced stability of the oil. These nanoparticles can scavenge and neutralize free radicals, which are highly reactive molecules responsible for oxidative damage [162]. By neutralizing these free radicals, the nanoparticles help to prevent or slow down the oxidation process, thus extending the shelf life of the oil. In addition, the oxidation mechanism of nanostructures investigated in [163] reveals that nanostructures with smaller particle sizes are more stable to oxidation. The experimental investigation reported in [164] also confirmed that the addition of nanoparticles to the base liquid can increase the time at which oil starts reacting to external factors. It was evident from the result in [164] that the addition of titanium oxide and graphite carbon nitride nanoparticles into the base liquid increases the oxidative onset of the liquid from 128 °C to 165 °C. Fullerene, allotropy of carbon is stable and has a good antioxidant property [165,166]. The application of fullerene nanoparticles has been investigated in several reports, especially on the enhancement of vegetable-based insulating oil [167,168]. In [169], the utilization of fullerene nanoparticles improved the oxidation characteristics of natural esters. The nanofluids prepared with these nanoparticles exhibited lower acid values after being subjected to aging compared to the base sample without nanoparticles. This outcome unequivocally demonstrates that the incorporation of fullerene nanoparticles into the base liquid enhances its thermo-oxidative stability.

4.3. Dielectric properties

4.3.1. Effect of different nanoparticles on the dielectric constant of natural esters

The dielectric constant is the real part of the complex permittivity in Eq. (9) which is related to the capacitive characteristics of an insulating oil [170–174]. It is related to the amount of energy an insulating oil can store. This property is slightly dependent on frequency but dependent on temperature. An increase in frequency leads to greater distortion in the system and disallows the displacement of the molecules from following the field. This makes the molecules of the liquid have an in-phase and out-phase component and the degree of polarization reduces which causes a retardation in the value of the dielectric constant [175].

$$\varepsilon^{*} = \varepsilon^{'} - i\varepsilon^{''} \tag{9}$$

Where $\varepsilon^{'}$ is the real part of the complex permittivity known as the dielectric constant and $\varepsilon^{''}$ is the imaginary part of the complex permittivity known as the loss factor [170,176].

In the same vein, temperature variation also has some effect on the dielectric capacity of an insulating liquid. An increase in temperature increases the kinetic energy of the oil molecules and the randomness consequently increases according to kinetic theory. This high degree of disorderliness affects the alignment of the oil molecules in the direction of the field and consequently affects the capacitance [9]. The effect of different nanoparticles on the dielectric constant of natural and synthetic esters has been studied and reported in the literature. In this section, the effect of different nanoparticles on the dielectric constant of natural esters is reported.

TiO_2 Nanoparticle

Numerous numbers of existing literature use TiO_2 nanoparticles when enhancing the insulating properties of vegetable oil-based liquids. This has been widely used in enhancing the properties of both insulating and engine oil. These nanoparticles have been used severally by researchers because of their unique properties like physical and chemical stability, environmental friendliness, easy accessibility, and cheap availability [177]. The effect of TiO_2 nanoparticles on natural esters was investigated in reference [36], and an increase in the dielectric constant was reported at low frequency for the first loading, however, the trend of the loading was not linear with the dielectric constant of the nanofluid. The effect of TiO_2 nanoparticles on the dielectric constant of methyl ester obtained from palm kernel oil was studied in reference [92]. The TiO_2 nanoparticles used are anatase with an average crystal size of 11 nm. The wide band gap of anatase over the rutile could be the choice for selecting anatase TiO_2 nanoparticles as additives in insulating liquids [178]. The loading of TiO_2 nanoparticles into the base oil increases the dielectric constant with a percentage increase of 36.5 % when 0.2 wt% of nanoparticles was added. Also, the addition of TiO_2 nanoparticles to the base liquid, natural ester was investigated in [179], and a slight increase in the dielectric constant of the base liquid was experienced.

SiO_2 Nanoparticle

The impact of silica nanoparticles (10–20) nm on the methyl ester synthesized from cottonseed oil was studied in [180], the addition of silicon oxide nanoparticles to the base liquid significantly enhances the deictic constant of the base liquid. This could be a result of the even distribution and quasi-uniform shape of the nanoparticles.

Al_2O_3 Nanoparticle.

Aluminum oxide nanoparticles have some peculiar properties like insulation, stability to thermal effects, and high melting point. Al_2O_3 nanoparticles were used in [181] for the enhancement of cotton-seed oil. A significant improvement in the dielectric properties of the base liquid was observed. On the methyl ester synthesized from palm kernel oil, the effect of Al_2O_3 nanoparticles of 18 nm was investigated in [93]. The nanofluid was prepared using the two-step method using oleic acid as the surfactant. The addition of nanoparticles to the methyl ester increases the dielectric constant of the based liquid.

Fe_2O_3/Fe_3O_4 Nanoparticle

In [36], a natural ester nanofluid was created by incorporating Fe_2O_3 nanoparticles. The nanofluids were formulated with different nanoparticle loadings of 0.01 g/L, 0.1 g/L, and 1 g/L in the base oil. The introduction of Fe_2O_3 nanoparticles into the base oil resulted in an increase in the dielectric constant of the base liquid, particularly at low frequencies. The dielectric properties of natural esters were enhanced in reference [103] through the addition of Fe_3O_4 oleic acid-coated nanoparticles. After the addition of nanoparticles, the dielectric constant of the base liquid experiences a notable increase of 8.6 %. The application of iron phosphide was also used in [182], and an increase in the dielectric properties of the natural ester base liquid was also reported. The observed rise in dielectric constant can be attributed to the combined effect of total polarization arising from the inner polarization of the nanoparticles, the orientation polarization of charged particles, and the base oil itself [183]. It is crucial to also acknowledge that in a situation when a surfactant or surface coating is employed, the type of materials used could also augment the dielectric constant of the base liquid.

4.3.2. Dielectric loss

The dielectric loss of insulating materials is related to the imaginary part of the complex permittivity in Eq. (10). In an insulating material (lossy medium), the dielectric loss originates from polarization and conduction [184]. The relationship between the imaginary part of complex permittivity and conductivity can be seen in Eq. (10) where σ is the conductivity, ω is the angular frequency and ε_o is the permittivity of free space [185,186]. Also, the loss due to polarization is related to imaginary complex permittivity by Eq. (11) where $\varepsilon^{''}_{pr}$ is the loss due to polarization. For a good insulating oil, the ratio of the conduction current to the displacement current must be far less than one [187]. In an insulating oil, the presence of impurities leads to an increase in the conductivity when the oil is subjected to an electric field. Insulation requires oils with low dielectric loss since high dielectric loss can eventually result in breakdown over an extended period. Natural esters have been reported to have dielectric loss higher than mineral oil and it was attributed to their polar nature [188,189]. The influence of nanoparticles on the dielectric loss of natural esters has been investigated by several researchers and the effects are addressed in this section.

$$\sigma = \omega\varepsilon_o\varepsilon^{''} \tag{10}$$

$$\varepsilon^{*''} = \varepsilon^{''}_{pr} - \frac{i\sigma}{\omega\varepsilon_o} \tag{11}$$

When nanoparticles are added to the base oil, the streamers generated because of the electric field are made to become immobilized by the nanoparticles which consequently decreases the streamer propagation and reduces the conductivity of the base oil [21,190]. Since dielectric loss originates from both conduction and polarization effects, the contribution from the part of conduction will be minimal due to the trapping of the mobile charges. This in turn leads to a decrease in the dielectric loss of the base liquid. In preparing a nanofluid with low dielectric loss, several factors like the type of nanoparticles, concentration, and dispersion of the particles in the base liquid are to be considered. In a situation where there is excess loading of nanoparticles, the particle–particle interaction increases and causes a continuity in the flow of the mobile charges which eventually increases the dielectric loss. Several reports have shown that loading nanoparticles to natural esters reduces dielectric loss [103,135,146,191,192]. The report from reference [91], utilizing Fe_3O_4 nanoparticles, demonstrates an improvement in enhancing the dielectric loss of rapeseed oil. The loading of Fe_3O_4 nanoparticles into the rapeseed oil reduces the dielectric loss when 0.004 wt% of nanoparticles was added. In [193], the decrease in dielectric loss was also reported when ZrO_2 nanoparticles (0.0015–0.0050) g/L were added to the base liquid. However, there are some reports in which the negative impact of nanoparticles on the base liquids is reported [114,194]. Due to diverse attributes related to different types of nanoparticles, it is important to investigate and optimize the effect of nanoparticles on the properties of the base liquid. In addition, the effect of surfactants used in the stability of the nanofluid on the dielectric loss of the base liquid needs proper investigation. The report in [97] gives an insightful contribution to the choice and effect of some selected surfactants on liquid insulators. The behavior of surfactants over time and temperature range is paramount because of the possibility of dissociation of the surfactants at high temperatures.

5. Dielectric breakdown

The breakdown of an insulating liquid occurs when the supply voltage is higher than the threshold voltage of the liquid. This is a critical factor to consider when choosing an insulating liquid. The breakdown event in a liquid dielectric is a stochastic event therefore, there is always a need to take the mean value of the breakdown voltage [78]. The setup for the AC breakdown voltage measurement and the test cell can be found in [195]. The test cell is filled with liquid insulators and the voltage is supplied at a certain interval based on the test standard. The oil molecules get ionized leading to more ions and electrons in the liquid. The ionization resistance of natural ester is low and this could lead to Joule heating which may eventually cause hotspots in the transformer [196,197]. Measuring the DC leakage current of insulating liquids enables the determination of the ionization resistance potential of the liquid insulator [198,199]. The dielectric breakdown strength of natural esters insulating oil has been enhanced by several researchers through the addition of nanoparticles [114,135]. The principle supporting the enhancement of liquid insulator strength when the nanoparticles are added to the base liquid was explained in [200,201] by the relaxation time constant of the nanoparticles and the streamer generation time scale of the base liquid. It was made known that nanoparticles can enhance the dielectric strength of the base liquid when the relaxation time constant of the nanoparticle is less than the streamer generation time scale of the base liquid. However, a limitation arises when attempting to explain the increase in the dielectric strength of the base liquid when employing a nanoparticle with a relaxation time constant greater than the streamer generation time scale [21,100,202]. Another proposed model called the deep potential trap model was proposed [203] and the application was utilized [204] on liquid dielectric, however, it was disproved by [205] using the shallow trap model which involves trapping and de-trapping of electrons. The limitation attributed to the Maxwell–Wagner relaxation was explained and justified in [206]. It was made known that the limitation attributed to the charging model by Maxwell–Wagner relaxation is not true as some other important factors influencing the charging mechanism like charging time and charging time constant are not considered. In [206], it was concluded that the field charging model, incorporating the Maxwell-Wagner relaxation phenomenon, successfully explains the principle behind the dielectric property enhancement of the base liquid when nanoparticles are introduced. Some recent applications of nanoparticles in the enhancement of natural ester AC breakdown voltage are summarized in Table 7. It is to be mentioned that several properties of nanoparticles like shape, size, electrical properties, type, and the thickness of the coating on the nanoparticle surface can influence the enhancement of dielectric strength of the base liquid. On the electrical properties of nanoparticles, it is proposed that conductive nanoparticles trap electrons in the liquid through a charging mechanism while both semiconductive and insulating nanoparticles trap electrons through a polarization process [207,208]. The influence of nanoparticle conductivity and permittivity is established in [209]. It is experimentally investigated that, nanoparticles with high conductivity and permittivity tend to enhance the dielectric properties of the base liquid more. The influence of nanoparticles with identical sizes but different properties was investigated in [210], the report affirmed that though nanoparticle sizes affect the electrical breakdown strength enhancement of the base liquids [211], nanoparticles' intrinsic nature also has a pronounced effect on the breakdown strength [139,212]. In addition, understanding the effect of surfactants and nanoparticle functionalization on the breakdown enhancement of the base liquid is of great importance [213]. The stability of surfactants at high temperatures and high electric field needs thorough investigation. Since the surfactants are used to create a continuity between the base liquids and nanoparticles, there is a tendency for bond breaking at high temperatures which consequently causes agglomeration and sedimentation of nanoparticles [88]. Furthermore, when selecting a surfactant, it is important to prioritize those with high stability to electric fields. This is crucial because certain surfactants can get ionized under high electric field conditions, leading to an increase in the conductivity of the natural ester base liquid [97]. The coating thickness on the surface of nanoparticles also plays an important role on the dielectric enhancement of the base liquids. This effect has been investigated in [214], however, there is need for further investigation on the effect of the nanoparticle coating thickness on the dielectric properties of the base liquids.

6. Partial discharge inception voltage (PDIV)

In contrast to breakdowns in solid and liquid insulators, which typically happen between high voltage and ground, partial discharge (PD) refers to a localized electrical discharge that only partially shorts the insulation between conductors. PD occurrences can take place either

Table 7
Effect of nanoparticle on the AC breakdown voltage of natural esters.

Base liquid	Nanoparticles	Nanoparticles loading			Particles range	Enhancement (%)	Ref
		wt.%	vol.%	g/L			
NEO FR3™	SiC	0.004	–	–	50 nm	37.3	[215]
Sunflower seeds ester	TiO_2	–	0.5	–	10 nm–20 nm	33.2	[135]
Soybean ester	TiO_2 and ZnO	–	–	0.20, 0.15	21 nm, <100 nm	63.11, 41.3	[98]
Palm ester	TiO_2 and ZnO	–	–	0.20, 0.20	21 nm, <100 nm	53.96, 44.4	[98]
Soybean	Al_2O_3	0.02	–	–	60 nm	27.9	[79]
FR3	TiO_2	–	0.03	–	<100 nm	12.90	[216]
Midel eN 1204	C_{60}	–	–	0.4	21 nm	7.8	[217]
FR3™	Al_2O_3 and SiC	0.004	–	–	50 nm, 50 nm	4, 16	[218]
FR3	ColMIONs, SiO_2	0.012			10 nm, 12 nm	20.62, -ve	[209]
Palm fatty acid ester	Fe_3O_4, TiO_2, Al_2O_3	–	–	0.01	15 nm–20 nm	45, 29, 34	[136]
FR3	Fe_3O_4		0.03		40.7 nm	24.5	[214]
Cotton seed oil	Hexagonal Boron Nitride (h-BN)	0.1	–	–	50 nm–70 nm	63.3	[219]
Vegetable oil	Eh-BN	0.01	–	–	50 nm–150 nm	4	[220]
Palm kernel oil Methyl ester	FeO_3	0.10	–	–	100 nm–250 nm	40	[34]
FR3	Fe_2O_3 and SiO_2	0.008	–	–	<50 nm, 12 nm	18.80, -ve	[105]
FR3	Al_2O_3 ZnO and SiC	0.004			50 nm	10.1, 20, 37.3	[210]

in proximity to a conductor or elsewhere [221]. Partial discharge in insulating liquid is an indication of non-uniformity in the electric field which may be due to the presence of voids, bubbles, and or degradation in the quality of insulating materials [222]. Therefore, partial discharge measurement is a substantial method for quality control, system monitoring, and high-voltage insulation materials maintenance. Among the benefits of partial discharge measurement are early detection of insulation issues, assessment of insulating materials quality, quality assurance during manufacturing, and non-destructive testing. Partial discharge in an insulating material is measured through conventional and unconventional methods. An example of a conventional method is the electrical method according to the IEC-60270 while the unconventional methods are Acoustic, Ultra-High frequency, and High-Frequency Current Transformers [223–225]. In addition, the combination of two or more of these methods called the hybrid method is also possible. Fig. 10 shows the schematic diagram of different methods of partial discharge measurement.

The partial discharge of palm-based nanofluid reported in [226] reveals the potential of Fe_2O_3 conductive nanoparticles. The partial discharge enhancement exhibited its optimal performance when nanoparticles were loaded in the base liquid at a low concentration (Fig. 11). At the medium and high concentration of nanoparticle loading, the partial discharge inception voltage experiences a decrease which could be attributed to an increase in particle–particle interaction which consequently bridges the flow of charges in the medium. The recent work on the enhancement of PDIV of refined, bleached, and deodorized palm oil (RBDPO) using Al_2O_3 was reported in reference [227]. The application of nanoparticles enhances the PDIV by 20 % when 0.001 % of nanoparticles were added to the base liquid. The influence of Fe_3O_4 and TiO_2 nanoparticles was observed on highly-refined palm oil, the partial discharge inception voltage increases as the loading of the nanoparticle increases [228]. The increase in the partial discharge inception voltage can be related to the trapping characteristic of the nanofillers which is also similar to the observation reported in [229]. This follows the same principle for the enhancement of the breakdown strength of the base liquid. Furthermore, excessive loading of the nanofillers to the base liquid of natural esters could cause overlapping of the electric double layers which consequently deteriorate the insulating strength of the base liquid. This overlapping can result in increased conductivity and reduced dielectric strength of the base liquid. Therefore, it is important to carefully optimize the concentration and dispersion of nanoparticles to ensure that the desired enhancement is achieved without compromising the insulation properties.

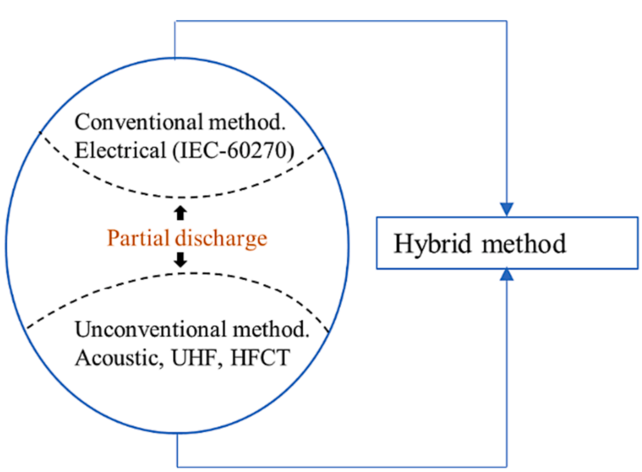

Fig. 10. Different partial discharge measurements.

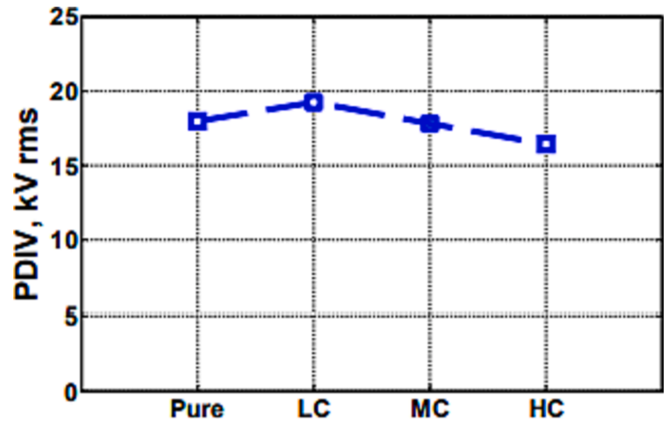

Fig. 11. Partial discharge inception voltage of palm oil based nanofluid [226].

7. Challenges and outlook

Although nanofluids possess outstanding characteristics related to cooling and insulation applications in transformers application, however, the application of nanofluids in transformers is yet an area of ongoing research and development. There are several extensive pieces of research made in the literature and efforts have been made by several researchers, however, some challenges are still attributed to nanofluids. These hitches need proper and extensive research to ensure the safety, reliability, and economic feasibility of the system.

7.1. Nanofluid long-term stability

The suspension and homogeneous dispersion of nanoparticles in the base liquid remain a critical concern in transformer applications. When nanoparticles aggregate or cluster together, the properties of the nanofluid can undergo significant changes, leading to a loss of its initial quality. This aggregation can result in sedimentation, impacting the heat transfer and insulating properties of the nanofluid. As a consequence, the performance and lifespan of the transformer may be affected. Therefore, achieving and maintaining a stable and well-dispersed state of nanoparticles within the base liquid is crucial for ensuring the desired enhancement and preserving the integrity of the transformer system. Effective strategies for preventing aggregation and sedimentation need to be developed to maximize the benefits of nanofluids in transformer applications and minimize any negative effects on performance and longevity.

7.2. Compatibility test

Gaining a comprehensive understanding of the long-term interaction between nanofluids and various components of a transformer, such as paper, coils, and the tank, is of utmost importance. It is vital to assess the degradation rate that occurs when all these components are taken into consideration. To achieve this, conducting test runs of nanofluids in a laboratory setting using a transformer prototype becomes essential. These experiments allow for the evaluation of the performance and compatibility of nanofluids with the transformer's materials and provide insights into the potential long-term effects and overall feasibility of utilizing nanofluids in practical transformer applications.

7.3. Health and environmental concerns

In a situation when an in-service transformer experiences an oil spill, it can result in the release of nanoparticles into the environment, posing potential health risks to both humans and aquatic life. Hence, it is crucial to establish appropriate methods for recycling the spilled nanoparticles in order to address this concern effectively. By implementing proper recycling procedures, we can contain and prevent the dissemination of nanoparticles, ensuring the safety of human health and the well-being of aquatic ecosystems.

7.4. Standard and regulation

In the field of transformer-related nanofluid research, there is currently a lack of standardized testing methods and guidelines for evaluating and implementing nanofluids. The absence of industry-specific standards and regulations hinders the widespread adoption of nanofluids in transformers and poses challenges in ensuring consistent performance and safety across different systems. Therefore, it is essential to establish industry standards and regulations tailored to nanofluids in transformers. This would not only facilitate their acceptance but also ensure uniform performance and safety standards across the industry.

8. Conclusion

Natural esters have garnered significant attention as a viable alternative for transformer insulation due to their exceptional properties in the recent past. Increasing focus on the application of natural esters in the field of transformer insulation holds immense benefits not only for the power industry but also for social and economic activities while adding value to the agricultural sector. This review extensively explores the potential of nanoparticles in enhancing natural ester for transformer applications. The investigation demonstrates promising results in terms of physicochemical and dielectric properties enhancement by incorporating nanoparticles into the base liquid of natural esters. However, before implementation, further investigation is required. Ensuring stability is a critical factor that requires thorough examination, along with the evaluation of stabilizing materials like surfactants and their compatibility with other transformer components. Additionally, considering environmental safety is of utmost significance when contemplating the application of nanofluids in transformers.

CRediT authorship contribution statement

S.O. Oparanti: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Visualization, Writing – original draft, Funding acquisition. **I. Fofana:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition. **R. Jafari:** Writing – review & editing, Validation, Resources. **R. Zarrougui:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Oparanti Samson Okikiola reports financial support was provided by Quebec Research Fund Nature and Technology. Issouf Fofana reports financial support was provided by Natural Sciences and Engineering Research Council of Canada.

Data availability

No data was used for the research described in the article.

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