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TOPICAL REVIEW

Dielectric Nanofluids for Transformers: A Review on Stability, Dielectric, Thermophysical, and Chemical Properties

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ABSTRACT Dielectric nanofluids are an advanced form of transformer liquid insulators with better performance as compared to traditional dielectric fluids. This review systematically examines the existing literature on stability of dielectric nanofluids, including influencing factors, stabilization methods, and long-term stability, as well as nanoparticle-enhanced insulating fluids in terms of dielectric, thermophysical, and chemical properties. This review shows that dielectric nanofluids have multifaceted advantages if size, agglomeration, and zeta potential can be controlled for improved stability, through surface functionalization, ultrasonication, and surfactants. However, aging effects necessitate periodic stability checks for industrial applications. Moreover, nanofluids offer improved dielectric properties (higher AC/Lightning impulse (LI) -breakdown voltage, higher partial discharge inception voltage (PDIV), streamers propagation inhibited, lower dissipation factor (tan δ)); enhanced thermal performance (higher thermal conductivity and heat dissipation); favourable physicochemical properties (moderate viscosity rise controllable through surfactants/nanoparticle reduced loading and higher flash/fire points than base fluids, the low pour points maintained, and chemical benefits (lower acidity, slower degradation of cellulose and higher flash points). While mineral oil based nanofluids exhibit the best performance. A standardized nanoparticle dispersion protocol and validation of stability over time in realistic operational scenarios is paramount for industrial uptake. As shown through experimental evidence, nanofluids have been shown to outperform the ordinary insulating oils in many parameters, with an average enhancement of approximately 21% in AC breakdown

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voltage. The review also provides an overview of challenges and directions for future research. Such improvements make nanofluids a candidate for the next generation of reliable, high-efficiency transformers.

INDEX TERMS Transformer, dielectric nanofluids, nanoparticles, breakdown, partial discharge, dissipation factor, thermal conductivity, viscosity, acidity, flash fire pour point.

I. INTRODUCTION

The high-voltage (HV) power grids are developing rapidly. Therefore, the need of high-performance transformers with more reliability under extreme operating conditions is ever-increasing [1]. Transformers are essential components in transmission and distribution networks, and account for about 60% of substation costs [2]. Their failure can lead to disastrous blackouts [3]. The insulating fluid is one of the most essential elements for transformer operation [4], [5]. In recent decades, mineral oil has been used as the major insulating fluid with both insulating and cooling functions. Nevertheless, typical mineral oils have intrinsic drawbacks such as low thermal conductance, aging during thermal or electrical cycles, environmental pollution as they are flammable and non-biodegradable [6], [7]. With this kind of disadvantages, it limits the transformer power density, efficiency, and lifetime, and new insulating fluids with better dielectric and thermal properties are expected.

Transformer oil degradation is a critical factor that affects the reliability of the grid. Studies shows that almost 32% of transformer failures are related to overheating [8], which shortens the expected operating life. Mineral oils are prone to chemical degradation under the action of high temperatures that persist over time, increasing the acidity, the appearance of sludge and the reduction of the dielectric strength [9], [10], [11]. Moreover, partial discharge activity, which leads to insulation aging, shortens lifetime and affects the performance of transformers [12], [13]. While vegetable oils and similar fluids have been investigated as alternative fluids, their poor dielectric and thermal properties prevent widespread use [14]. Consequently, significant advancements are essential to develop cutting-edge insulating fluids that enhance thermal and dielectric performance while addressing safety and environmental issues.

Nanotechnology promises transformation, where it holds the key to transformer insulating fluids such as nano-dispersed insulating fluids. Nanofluids, stable suspensions of nanoparticles in base fluids, were first introduced by Choi [15], which showed a 350% increase in thermal conductivity with copper nanoparticles in water. Nanofluids have been used in many areas such as energy [16], [17], biomedicine [18], [19], and electronics [20], [21] from that time. Dielectric nanofluids, in which nanoparticles suspended in mineral oil or other base fluids, have demonstrated significant enhancements in breakdown strength [7], [22], [23], thermal conductivity [24], [25], and aging resistance in the field of HV insulation [26]. Unlike micron-sized particles that settle and decrease insulation properties upon sedimentation and agglomeration, nanoparticles do not sediment and agglomerate spreading uniformly, thus contributing to better heat transfer and dielectric properties without risking dispersion stability.

Nanofluids stability is the key aspect which governs their applicability in transformer. Important issues are the particle agglomeration, sedimentation, and degradation under operational stresses over long-term [27], [28], [29]. In order to improve stability, a number of approaches have been proposed that range from the addition of surfactants, ultrasonication, and surface functionalization of nanoparticles [30], [31], [32]. Surfactants can minimize the interfacial tension to inhibit particle aggregation, and ultrasonication guarantees that particles remain uniformly dispersed by breaking up on nanoparticle clusters. Also, surface functionalization techniques like silane grafting are aimed at improving compatibility of the nanoparticles with base fluids [33], [34], hence increasing dispersion stability of dielectric nanofluids. It is crucial to understand the mechanisms of stabilization so that nanofluids could survive the extreme environment in transformers with minimum decline in the performance over time.

However, in addition to stability, the dielectric and thermophysical properties of dielectric nanofluids are critical factors which determine its applicability in transformers. Experimental studies reveal that nanoparticles significantly increase breakdown voltage and reduce partial discharge (PD) activity [31]. Furthermore, dielectric nanofluids are known to enhance thermal conductivity, mitigating the negative impacts of viscosity, creating better heat dissipation and maintaining flow dynamic [35], [36], [37]. However, the relationship between nanoparticle concentration, size, and dielectric performance remains an active area of research. While excessive nanoparticle loading may cause high viscosity and hinder cooling effectiveness, insufficient concentrations may fail to produce the desired performance improvements. A systematic investigation of these properties is necessary to optimize dielectric nanofluids for real-world transformer applications.

This review explores dielectric nanofluids, encompass their composition, stability, dielectric characteristics, thermophysical characteristics, chemical properties, challenges in real-world applications, and prospective research directions. Section II delves into the composition and classifications pertaining to base fluids, nanoparticles, and surfactants utilized in dielectric nanofluids. Section III delves into the stability of dielectric nanofluids, exploring the various factors that influence stability, the methods employed to enhance, and studies on long-term stability and aging effects. Meanwhile, Section IV outlines essential performance metrics, including breakdown strength, partial discharge, dissipation factor, thermal conductivity, viscosity, flash, pour, and fire points, as well as acidity. Ultimately, Section VI addresses the obstacles and prospective avenues for research, highlighting the importance of scalability, enduring reliability, and ecological sustainability. This review seeks to synthesize recent advancements and pinpoint essential research gaps to steer the evolution of next-generation dielectric nanofluids for superior transformer insulation performance.

II. COMPOSITION AND CLASSIFICATION

A. BASE FLUIDS

Dielectric fluids serve a crucial role in various power system components, including transformers, capacitors, tap changers, reactors, bushings, and switching devices, among others [38], [39]. These fluids deployed to serve two purposes, enhancing the dielectric strength of the environment around it, and facilitating the dissipation of heat energy generated by losses. For the reliable working conditions, it is extremely important that the physio-chemical characteristics of the dielectric fluid used are highly stable [40]. The failure of equipment due to low-quality insulating fluid in high voltage networks can cause widespread electricity blackouts and potentially result in significant financial liabilities [41].

The insulating fluids utilized by transformers have undergone development throughout the years [42]. Power transformers often employed insulating liquids generally including mineral oils, natural ester liquids, silicone oils, and synthetic ester liquids. Mineral oil, a petroleum-derived fluid, has been widely used in this business for an extended period [43]. Its superior resistance to oxidation, low viscosity, availability, and affordability make it the most prevalent dielectric fluid. Nonetheless, it has adverse characteristics like lower moisture saturation, low flash and fire points, and poor biodegradability [44]. Conversely, highly biodegradable natural ester liquids have been progressively utilized as dielectric fluids recently. Additionally, they demonstrate enhanced characteristics like elevated flash and fire points, significant moisture saturation, and a retardation of paper deterioration [45], [46]. Nonetheless, many adverse characteristics include increased viscosity and susceptibility to oxidative instability [14], [47]. Silicone oils, as a category of dielectric fluids, possess significant gas absorption during partial discharges, elevated fire and flash points, and considerable thermal and oxidation stability. However, they also display adverse characteristics, including high viscosity at elevated temperatures, inadequate lubrication, and extremely low biodegradability [48]. Synthetic esters provide advantageous characteristics, including elevated breakdown voltage, significant moisture saturation, high flash and fire points, superior oxidation stability, notable biodegradability, and effective lubricating qualities [39]. The primary drawback of synthetic ester liquids is the higher cost, which therefore restricts their use [49]. Table 1 presents a comparative analysis of the characteristics of different dielectric base fluids.

Investigations on the advancement of dielectric fluids persist with applications of future generations [16]. The most notable examples are those that include the incorporation of nanoparticles into the aforementioned base liquids [52]. The resulting suspensions are referred to as nanofluids. In 1995, Choi and Eastman performed fundamental research on nanofluids, where the name ''nanofluid'' was first used. In subsequent years, the advantageous characteristics of nanofluids prompted their investigation across diverse sectors, including energy systems, machinery, materials science, power systems, medical applications, and electronics, etc [52]. The use of dielectric nanofluids is a relatively recent area of study, gaining momentum around the middle of the 2010s. The transformer industries mostly utilize standard products, resulting in inadequate market awareness for dielectric nanofluids.

TABLE 1. Various dielectric base fluids and their properties [50], [51].

Properties	Natural ester	Mineral oil	Silicon ester	Synthetic ester
Dielectric				
Breakdown voltage [kV]	>35	>30	>40	>45
Dissipation factor @ 90 °C	<0.05	<0.005	<0.001	<0.03
Thermal				
Specific heat [J/kg.K]	1500–2100	1860	1510	1800–2300
Physicochemical				
Density [g/cm^3] @ 20 °C	<1.0	<0.895	0.95–0.97	<1.0
Pour point [°C]	< -15	< -40	< -40	< -45
Flash point [°C]	>250	>135	>240	>250
Kinematic viscosity [cSt] @ 100 °C	<10	3	16	6
Kinematic viscosity [cSt] @ 40 °C	<50	<12	40 ± 4	<35
Water content [mg/kg]	<200	<30	<50	<200

Nevertheless, favourable outcomes from research indicate that dielectric nanofluids has significant promise in the electrical sector. This research is crucial for the transformer industry. Research has been conducted using various base insulating fluids; still, the findings using mineral oils seem most promising for future generations. Moreover, mineral oils are now amongst the most sought-after products globally for use as insulating fluids, because their cost is lower than that of other fluids [53]. The incorporation of nanoparticles into the fluids results in an undesired increase in their viscosity [54]. Mineral oils have a reduced viscosity compared to other dielectric fluids, including ester liquids, making them more favourable [55].

B. NANOPARTICLES

Nanofluids develop by dispersing solid nanometre sized particles (i.e., < 100 nm) in base fluids [56]. Basal fluids may be mineral oils, natural or synthetic ester liquids, or silicone oils, whereas nanoparticles may be conductive, semiconductive, insulative, and their combinations (hybrid nanoparticles) [31], [57]. Figure 1 presents the categorization of nanoparticles employed in transformer fluids as documented in the literature.

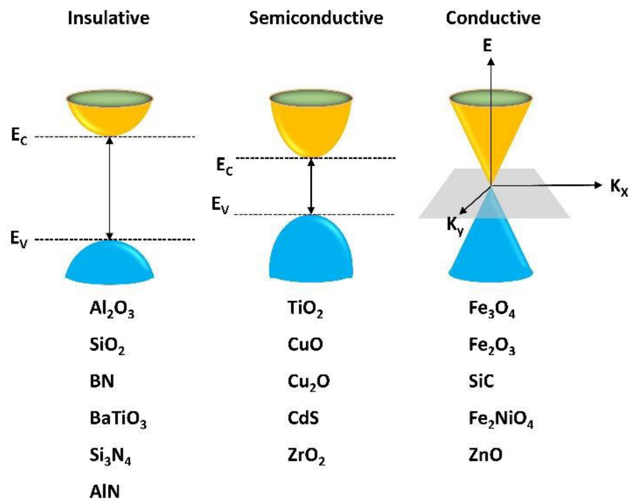

FIGURE 1. Types of nanoparticles used in dielectric nanofluids.

C. SURFACTANTS

Surfactants are required for the preparation of stable nanofluids, but their impacts are often disregarded when assessing the boosting effect of dielectric nanofluids. Coating them with a surfactant is an important step in assuring the long-term dispersion stability of oil-based nanofluids [58]. Many studies observed that adding surfactants to dielectric nanoparticle suspensions improves nanofluid stability and dispersion [30], [59]. This indirectly leads to the improvement of nanofluid dielectric and thermal properties. Surfactants utilized in dielectric nanofluids are categorized as seen in Figure 2a [60]. Positive and negative charge groups on its head suggest cationic and anionic surfactants, respectively. The absence of a charge group on its head implies a non-ionic surfactant. Both charge groups on the head suggest an amphoteric surfactant. Surfactants stabilize nanofluids in two ways: electrostatic and steric [61]. Electrostatic stabilization (Figure 2b) is possible using ionic surfactants. Charged nanoparticles attract counter-charged surfactant particles, resulting in Coulomb repulsive forces between nanoparticles, which oppose attractive van der Waals forces between them [62]. Steric stabilisation (Figure 2c) is a term used to describe additives that use non-ionic surfactants to prevent suspension coagulation. Surfactants in nanofluid suspension enhance nanoparticle surface characteristics.

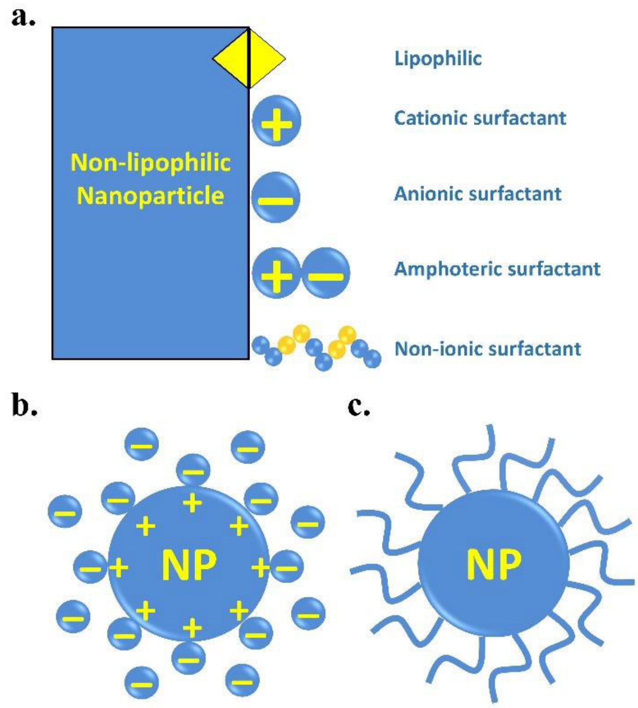

FIGURE 2. (a) Types of surfactants according to polarity of their head group [60] and stabilization of nanoparticles using surfactants (b) Electrostatic and (c) Steric [63].

A variety of surfactants are used in dielectric nanofluids depending on the nanoparticle. Anionic surfactants (i.e., oleic acid), are effective with metal oxides (such as Al_2O_3 [64], TiO_2 [65], Fe_3O_4 [66], SiO_2 [67], and ZnO [68]) because they chemically adsorb onto nanoparticle surfaces, improving dispersion stability, preventing oxidation, and enhancing AC breakdown voltage. Cationic surfactants (i.e., CTAB), are suitable with SiO_2 [69], Al_2O_3 [69], TiO_2 [70], Fe_3O_4 [71], CuO [71], and ZrO_2 [72], in consequence of the same purpose, where use of a cationic surfactant brings about electrostatic repulsion, and so improves stability. However, in some cases, they might increase charging current [73], which results in inconsistent AC BDV measurement results. Non-ionic surfactants (i.e., Sorbitan Monolaurate and Span 80) are generally combined with TiO_2 and SiO_2 nanoparticles [73], [74], which were selected due to their steric hindrance properties that prevent phase separation while showing less electrical conductivity, which could lead to high insulating properties.

III. STABILITY OF DIELECTRIC NANOFLUIDS

A. FACTORS AFFECTING STABILITY (PARTICLE SIZE, AGGLOMERATION, ZETA POTENTIAL)

The size of nanoparticles significantly affects their dispersion and sedimentation rate in dielectric nanofluids. Studies examined the influence of nanoparticle size on the characteristics of dielectric nanofluids [53], [75]. These studies indicated that smaller nanoparticles exhibited superior performance relative to larger nanoparticles at the nanometre scale. Figure 3 compares the AC breakdown voltages of CNT nanofluids with two different diameter sizes of CNTs: < 8 nm and > 20 nm [53]. The results show that CNT nanofluids with smaller diameter CNTs (< 8 nm) achieved higher breakdown voltages compared to the larger diameter CNTs (> 20 nm). Specifically, at a concentration of 0.01 g/L, the CNT nanofluid with < 8 nm CNTs reached the highest breakdown voltage of 51.68 kV, which is a 70.50% improvement compared to the > 20 nm CNT nanofluid at the same concentration. This may be attributed to smaller size of CNTs enables more uniform dispersion and reduces agglomeration, which are key factors in enhancing the breakdown voltage.

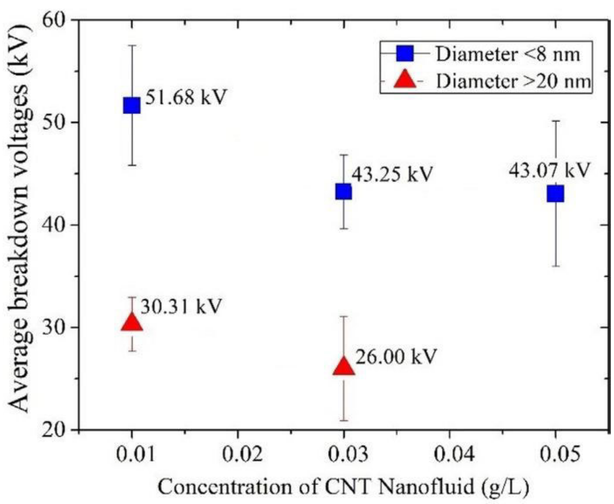

FIGURE 3. **The mean AC breakdown strength of dielectric nanofluids corresponds to two distinct CNT nanoparticle sizes [53].**

Smaller nanoparticles generally leading to higher Brownian motion, which helps maintain uniform dispersion and minimizes sedimentation [76]. The improvement noted in this scenario stems from the nanoparticles' higher surface area relative to their volume, which promotes greater interaction with the surrounding fluid and helps minimize particle clumping [77]. Smaller particles exhibit elevated surface charge density, thereby enhancing the intensity of electrostatic repulsive forces that inhibit particle aggregation [78]. Nonetheless, the examined studies indicate that size must be maintained within an optimal range. If the nanoparticles are excessively diminutive, robust van der Waals forces lead to aggregation, whereas larger particles will descend due to gravitational influence [31]. Table 2 summarizes the optimal size ranges of various nanoparticles that demonstrated the best performance in dielectric nanofluids. While materials like graphene perform better even at sizes >500 nm [79], due to their high aspect ratio; most other nanoparticles exhibit optimal performance below 100 nm, where surface area enhanced dispersion behavior. Notably, several studies report superior performance at sizes <10 nm [80], likely due to stronger particle–fluid interactions at the nanoscale.

Agglomeration of nanoparticles is one of the most important problems that cause the dispersion instability of dielectric nanofluids over time. The main challenge is attaining a uniform suspension of nanofluids, as there is often the formation of aggregates in nanoparticles due to Van der Waals forces which can cause sedimentation and loss of functional properties [2]. One of first requirements for the practical application of nanofluids is the long-term stability of nanoparticles dispersion. Over time, nanoparticles can undergo agglomeration and/or sedimentation, leading to a decrease in homogeneous dispersion of the nanoparticles in base fluid [1].

TABLE 2. **Nanoparticle sizes yielding optimal performance.**

Sr. No.	Nanoparticles	Nanoparticle size	Ref.
1.	Graphene	> 500 nm	[79]
2.	SiO_2, h-BN, Al_2O_3, and Fluorinated BNNs	100-500 nm	[32], [79], [81], [82]
3.	ZrO, SiC, and TiO_2	50-100 nm	[83]–[85]
4.	ZnO, CdS, Co_3O_4, CeO_2 + MWCNTs, MWCNTs, TiO_2, SiC, and Al_2O_3	10-50 nm	[27], [83], [84], [86]–[99]
5.	TiO_2, CdS, MWCNTs, and Al_2O_3	< 10 nm	[37], [84], [88], [95]

The image in Figure 4a, depicts a homogenous distribution of nanoparticles, with no signs of agglomeration or sedimentation being visible. Compared to the pure base fluid, the homogeneous nanofluid shows increased breakdown voltage due to the greater branching of the charge paths. Nanoparticle agglomeration can shorten the charge paths in the nanofluid, which reduces the breakdown voltage [100], [101]. Figure 4b mentions the case of the agglomeration of nanoparticles. In this case, the nanoparticles were colliding with each other in the liquid insulation medium and agglomerating over time. This allows for an increase in both the overall diameter and mass of the agglomerated particles, making them more susceptible to gravitational sedimentation [102], [103]. Figure 4c shows the scenario of sedimentation with particle agglomeration. These agglomerated nanoparticles aggregate and form concentrated areas as they settle to the bottom of the fluid. Agglomeration and sedimentation of the charged nanoparticles can form thicker and densified paths for charge percolation, which affect the nanofluid breakdown voltage negatively. Agglomeration and sedimentation reduce the surface area of nanoparticles, resulting in reduced thermal conductivity [104], [105]. Agglomeration and sedimentation can reduce the flash, fire, and pour points of nanofluids compared to base fluids [106], [107].

The zeta potential plays a crucial role in determining the stability of nanofluids. Zeta potential refers to the electric potential at the slipping plane of a particle in a colloidal system. It is a key indicator of the electrostatic repulsion between particles. Nanofluids are deemed stable when the zeta potential exceeds ±30 mV [108]. An elevated positive or negative zeta potential value signifies enhanced stability of the nanofluid, effectively inhibiting the occurrence of agglomeration and sedimentation of the nanoparticles. The nanoparticles exhibiting a significant zeta potential, whether positive or negative, encounter a robust repulsive force. This force ensures their effective dispersion within the base fluid, inhibiting the formation of larger clusters. A low zeta potential value indicates that the nanoparticles are prone to agglomeration, which results in reduced stability of the nanofluid.

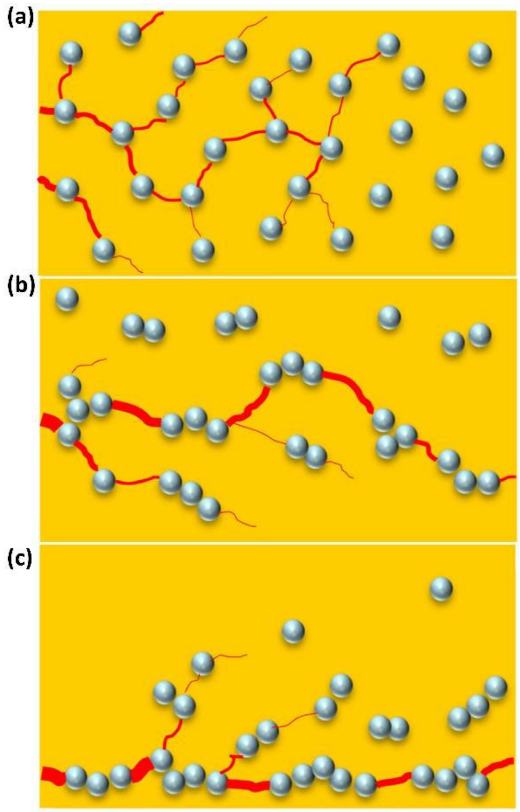

FIGURE 4. Illustration: (a) Uniform distribution of nanoparticles, where greater branching of the charge paths and (b) Agglomeration and (c) Sedimentation of nanoparticles causing the charge paths to be further concentrated and shortened [1].

B. METHODS TO ENHANCE STABILITY (SURFACTANTS, ULTRASONICATION, SURFACE FUNCTIONALIZATION)

1) SURFACTANTS

The enduring stability of dielectric nanofluids is essential for preserving their thermal and electrical efficacy in transformer applications. The studies examined underscore that the aggregation and sedimentation of nanoparticles pose significant challenges, with various techniques implemented to improve the stability of nanofluids. The literature highlights three essential methods: the addition of surfactants, ultrasonication, and the functionalization of surfaces. Surfactants play a crucial role in minimizing surface tension between nanoparticles and the base fluid, enhancing dispersion and inhibiting aggregation. The analysed research indicates that surfactants function by establishing a barrier around nanoparticles, thereby inhibiting direct contact and the formation of clusters. Surfactants function through electrostatic stabilization for ionic surfactants and steric stabilization for non-ionic surfactants, as depicted in Figure 5a and b, respectively. Electrostatic stabilization generates repulsive forces among nanoparticles, whereas steric stabilization inhibits aggregation by establishing a physical barrier.

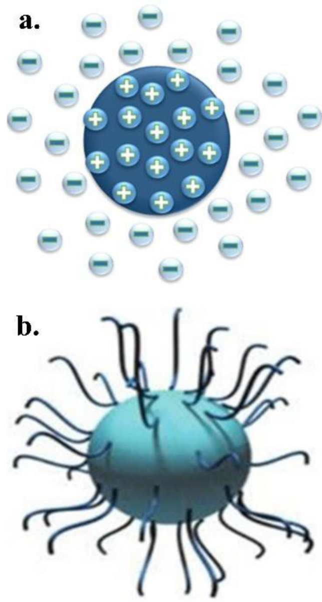

FIGURE 5. Illustration (a) Electrostatic and (b) Steric stabilization mechanism [109].

Surfactants have an important function in increasing nanofluid stability. The choice of surfactant is critical for a particular nanoparticle and base fluid combination because the effect of different surfactants on the stability of dielectric nanofluids varies considerably. Surfactant concentration is also important. Findings of zeta potential studies with and without surfactant in synthetic ester-based nanofluids having different concentrations of silica nanoparticles are provided in Figure 6 [30]. It further indicates the effect of different surfactant concentrations (CTAB, Oleic acid, span 80) added to the optimal concentration of 50 mg/L of silica nanoparticle. When the cationic surfactant CTAB was incorporated, the zeta potential became more positive. The surfactants being non-ionic, oleic acid and span 80 significantly exhibited negative zeta potentials with span 80 retaining the highest negative zeta potential. The more negative zeta potential of span 80 reported is possibly due to its higher solubility in the base ester liquid owing to the presence of the hydrophilic 3-OH group in its molecular structure [110].

Few researchers are able to obtain stable dielectric nanofluids without the use of a surfactant [37], [85], [111], [112],

TABLE 3. Surfactant-treated dielectric nanofluids with concluding remarks on dispersion stability.

Base oil	Nanofiller	Surfactant	Concluding remarks on dispersion stability	Ref.
Synthetic ester and natural ester	Fe_3O_4, Co_3O_4, & FeP	Oleic acid	The base oils used were synthetic ester oil and natural ester oil. The surfactants coat the nanoparticle's active surface, reducing coagulation and increasing stability.	[117]
Mineral oil	SiO_2 and Al_2O_3	CTAB	Silica nanofluids are sedimented in the absence of a surfactant. The nanofluids with CTAB at 0.1 wt.% showed the least sedimentation.	[69]
Cottonseed oil	Graphene oxide	SDS	UV–Vis optical spectroscopy was used to assess cottonseed oil nanofluid stability. The 1 Graphene oxide: 1 SDS ratio nanofluid showed the highest stability by showing the lowest absorbance.	[44]
Transformer oil	ZrO_2	CTAB	Dispersion stability was assessed using the zeta potential, which first increases with the increase in CTAB concentration and subsequently drops, the optimum zeta potential level (maximum value) was obtained at 0.3%.	[72]
Mineral oil	TiO_2	CTAB	The dispersion of nanoparticles in the mineral base oil used was greatly affected by surfactant concentration. Low surfactant concentrations had less aggregation and better dispersion than situations without or with excess surfactant.	[104]
Transformer oil	Graphene & CNT	Oleic acid	Depending on nanomaterial content, the surfactant is used at 0.5-2 mL per 500 mL of oil. Surfactant at such low concentrations had little influence on base oil breakdown strength.	[118]
Mineral oil	Al_2O_3	Oleic acid	Mineral oil based oleic modified showed good dispersion stability at 0.03 wt.% nanoparticle and 0.1 wt.% surfactant nanofluid.	[119]
FR3 natural ester	Fe_2O_3	Oleic acid	FR3 natural ester oil-based synthesized oleate-coated nanoparticles were stable, even after 16 months. Oleic acid-coated commercial nanoparticles were sedimented in a short period of time.	[115]
Mineral oil	Al_2O_3	SDBS	Mineral oil-based nanofluids with a surfactant weight percentage of 0.1% are more stable than those with a surfactant weight percentage of 1.0%.	[120]
Palm oil and coconut oil	Fe_3O_4, CuO, and Al_2O_3	CTAB	Transmission electron microscopy showed that CTAB improved nanoparticle dispersion in refined, bleached, and deodorized palm oil and coconut oil.	[71]
Cottonseed oil	Al_2O_3	SDBS	SDBS induced repulsion force between nanoparticles, improved nanoparticle dispersion in cottonseed oil and thus improved thermal and dielectric characteristics.	[58]
Ester and mineral oil	TiO_2	CTAB/Oleic acid	In a combination of ester and mineral oil nanofluid, CTAB as a surfactant exhibited improved properties and increased stability compared to findings obtained with oleic acid as a surfactant.	[121]
Mineral oil	Fe_3O_4	Carboxilic acid	Carboxyl functionalized surfactants seem better suited for natural ester oil, while non-carboxylic surfactant is suited for nanofluids prepared from low polarity fluids like mineral oil.	[122]
Vegetable oil	TiO_2 and Al_2O_3	Oleic acid	Nanoparticles were uniformly dispersed in a mineral and vegetable oil blend.	[47]
Shell Diala S2 transformer oil.	TiO_2	CTAB	Surfactants have not played a significant role in attaining stability. It increased breakdown strength by creating a rigid interfacial zone around nanoparticles.	[123]
Synthetic ester	Fe_2O_3, TiO_2 and Al_2O_3	Oleic acid	Nanoparticles did not agglomerate or lose their size in synthetic ester oil. Thus, surfactants stabilized dispersions for longer periods.	[124]
Mineral oil, synthetic ester, and natural ester	TiO_2	Monolaurate sorbitan	Nanofluid dispersion stability was good. Density and thermal expansion were unaffected by infused surfactant-treated nanoparticles.	[55]
Mineral oil	Al_2O_3	Oleic acid	Nanoparticles dispersed in mineral oil and the back ends of surfactant molecules repel each other to prevent particles from agglomeration.	[125]
Mineral oil	Iron oxide	Oleic acid	Surfactant stabilized nanoparticles in mineral oil (Mogul, TRAFO CZ-A, Paramo, CZ).	[126]
Mineral oil	Fe_3O_4	Oleic acid	Mineral oil was used as a base oil. At optimal temperature, dielectric properties were improved.	[127]
Mineral and synthetic ester	Fe_3O_4	Oleic acid	Nanoparticles were dispersed and stabilized in mineral oil and synthetic ester using a surfactant.	[128]
Mineral oil	Fe_3O_4	Oleic acid	Nanoparticles were homogeneously dispersed in mineral oil.	[129]
Mineral oil	Nano-silica	Plasma (matter)	Good dispersibility and stability of nanofluids were shown to be the result of significant changes in the surface chemistry of nanoparticles due to plasma treatment of nano-silica.	[34]
Vegetable oil	Fe_3O_4	-	In the insulating vegetable oil, the surface-modified Fe_3O_4 particles were effectively dispersed.	[130]
Mineral oil	Fe_3O_4, TiO_2 & their mixture	Oleic acid	Titania nanoparticles were dispersed well in service-aged oil.	[65]
Mineral oil	Fe_3O_4	-	In the presence of a magnetic field, commercial ferrofluid nanofluid containing surfactant dispersed in mineral oil exhibited good stability.	[131]
Natural ester	Fe_3O_4	Oleic acid	Physical adsorption and chemical bonding bring together the oleic acid molecules and the Fe_3O_4 nanoparticle surfaces. Surface-modified Fe_3O_4 are uniformly dispersed in the insulating natural ester.	[132]
Naphthenic transformer oil	TiO_2	Oleic acid	The nanospheres spread evenly when introduced to the naphthenic transformer oil, but nanorods prefer to contact each other.	[133]
Polyalphaolefin oil	MgO	Span 80	Surfactants maintained nanoparticles were dispersed in polyalphaolefin oil and formed enclosures to prevent nanoparticle collisions and minimize deposition.	[134]
Cottonseed oil	Graphene	SDBS	Compared to cottonseed oil nanofluids with a 30-minute ultrasonication duration, 60-minute nanofluids showed more uniform dispersion and stable nanoparticle suspension.	[103]
Mineral oil	TiO_2	Steric acid	The dispersibility of TiO_2 nanoparticles functionalized by stearic acid in the mineral oil has been observed to be significantly enhanced.	[135]

[113]. However, there are many studies that used surfactants to prevent agglomeration. In [114], the cobalt ferrite nanoparticles were coated with surfactants to prevent agglomeration and oxidation from ambient oxygen. Various combinations of nanoparticles in different dielectric base fluids with different surfactants are listed in Table 3; concluding remarks on dispersion stability are listed briefly. Numerous surfactants, such as cetyltrimethyl ammonium bromide (CTAB), oleic acid, sodium dodecyl sulfate (SDS), sodium dodecylbenzene sulfonate (SDBS), stearic acid, carboxylic acid, monolaurate sorbitan, plasma (matter), C2, C18, and span 80 were employed to prevent agglomeration or sedimentation and boost stability.

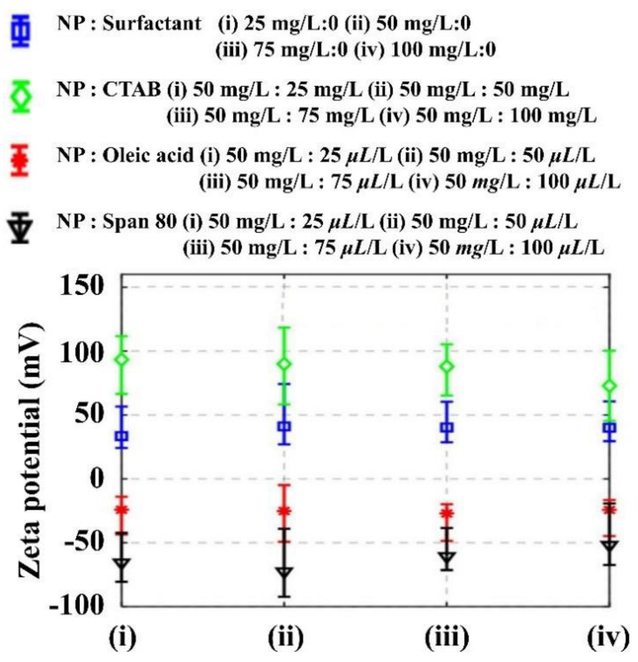

FIGURE 6. Zeta potential of nanofluids without surfactant at different SiO_2 concentrations and the optimal nanofluid (50 mg/L SiO_2 concentration) at different surfactant levels [30].

In all these studies, oleic acid emerges as the primary surfactant utilized, demonstrating notable effectiveness with metal oxide nanoparticles (i.e., Fe_3O_4, Al_2O_3, TiO_2) in both mineral and ester-based liquids. It enhances long-term stabilization through adsorption or chemical bonding to the surface, forming a barrier that inhibits the agglomeration of nanoparticles. In the case of natural ester liquids like FR3, oleic acid coated Fe_2O_3 nanoparticles demonstrated stability for up to 16 months [115], indicating that the choice of surfactant and the compatibility with base oil significantly influence stability. Similarly, CTAB demonstrated improved dispersion in mineral oil [69], palm [71], and coconut oils [71], with this effect becoming more pronounced as the concentration was optimized. However, this behaviour was constrained beyond the optimal concentration [72], due to the formation of micelles or excessive ionic shielding [116]. Furthermore, the choice of surfactant influenced by the polarity of the base fluid and the surface chemistry of the nanomaterials. Characterizations of dispersibility were conducted at varying concentrations utilizing UV–Vis spectroscopy [44], zeta potential [72], and electron microscopic [71] techniques. In conclusion, the findings demonstrate that stable dielectric nanofluids can be achieved through the careful selection of base oil, types and dosages of surfactants, and that surface modification is crucial in the development of all-dielectric nanofluids for sustained electrical and thermal applications.

2) ULTRASONICATION

Ultrasonication is important to disperse the nanoparticles, to break nanoparticle clusters and to exfoliate nanosheets in dielectric nanofluids [136]. However, optimizing the ultrasonication parameters is the most important step for obtaining desired results to stabilize dielectric nanofluids [31]. Figure 7 represents the interactions of ultrasonic energy during ultrasonication process which results in the creation of cavitating bubbles in the sample [137]. Some of the main aspects shown in the figure are: (1) Bubble nucleation: The ultrasonic waves creates and speeds up various microscopic bubble inside the liquid. (2) Bubble expansion and implosion: The bubbles expand due to ultrasonic waves and then collapse rapidly, creating localized high temperature and pressure. (3) The formation of microjets: The collapsing bubbles generate microjets that travel at high velocities and shear into the surrounding fluid and particles. (4) Interparticle collision: the collision frequency of dispersed particles is high due to microjets and fluid movement. (5) The radical formation: The temperatures during bubble collapse are thought to be so extreme that they will lead to radical formation. These distinct physical and chemical impacts of cavitation lead to the efficient dispersion, deagglomeration, and homogenization of nanoparticles in the base fluid during the ultrasonication.

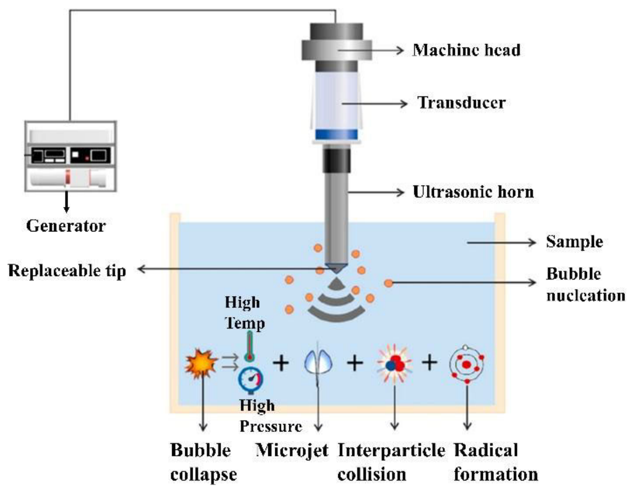

FIGURE 7. Illustration of ultrasonication working principle [137].

Figure 8 visually represents the diverse microscopic forces acting upon a single nanoparticle suspended in base fluid, as well as the interaction with adjacent nanosheets, nanorods and other nanoparticles [138]. Gravitational force (proportional to the cube of the nanoparticle radius) which causes sedimentation of nanoparticles due to the density difference between the nanoparticles and base fluid [82]. Brownian motion force (inversely proportional to the nanoparticle radius) which counteracts the gravitational sedimentation and helps disperse the nanoparticles [139]. Van der Waals attractive force (inversely proportional to the nanoparticle radius) which can cause agglomeration of nanoparticles [78], [140]. Viscous force (proportional to the nanoparticle radius) which also aids in reducing nanoparticle sedimentation [141]. The figure illustrates how these diverse microscopic forces interact to determine the dispersion stability of the nanoparticles in the base fluid. Ultrasonication is essential for enhancing the stability of nanoparticle dispersion in dielectric nanofluids by efficiently regulating the many microscopic factors influencing the nanoparticles, including the force of gravity, Brownian movement, sedimentation velocity, force of van der Waals, and viscous forces. Enhancing the sonication parameters (duration, power, frequency, and amplitude) augments the stability characteristics (reduced nanoparticle cluster sizes, elevated zeta potential, and diminished sedimentation rate) [31].

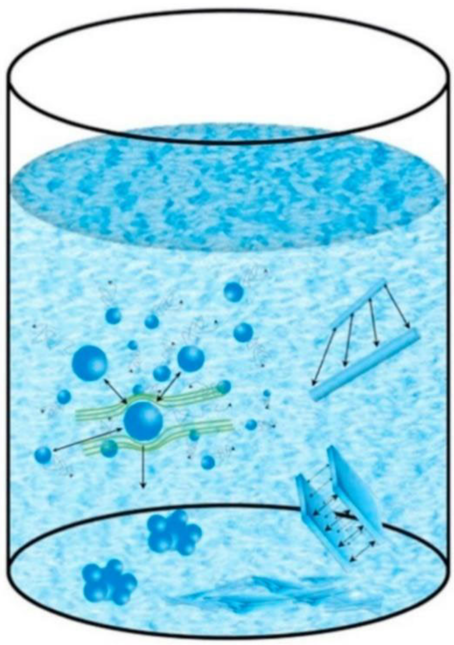

FIGURE 8. Illustration depicting the various nanoscale forces influencing an individual nanoparticle within a basal fluid, along with its interactions with nearby nanosheets, nanorods, and surrounding particles [138].

The selection of ultrasonication technique (probe versus bath) and the time is significantly influenced by the characteristics and structure of the nanomaterial as shown in Table 4 [31]. Carbon (i.e. Graphene, MWCNT, etc.) and hybrid nanoparticles (i.e., Mixture of more than one nanoparticle mixture) frequently take advantage of the powerful energy provided by probe sonication [84], [88], [97]. In contrast, metal oxides, compound nanoparticles, 2D materials (i.e., non-carbon materials like h-BN), and functionalized (i.e., functional group-attached) nanoparticles can effectively employ both techniques [27], [89], [98]. Nanoparticles with size below 10 nm can be uniformly distributed through the application of high-power probe sonication [142]. Nanoparticles ranging from 10 to 100 nm in size can be dispersed effectively using either ultrasonic bath or probe sonication techniques. For even larger nanoparticles (>100 nm), bath sonication is preferred so as to provide homogenous yet gentle energy distributed [31]. Bath sonication demonstrated remarkable dispersion capabilities for low concentrations of nanoparticles (≤0.01 g/L, vol%, wt%) [143], whereas both bath and probe sonication are effective for the low concentration range of nanoparticles (0.01-0.1 g/L, vol%, wt%) [37]. For intermediate (0.1-0.5 g/L, vol%, wt%) and elevated (>0.5 g/L, vol%, wt%) concentrations of nanoparticles, probe sonication is the method of choice [31].

The zeta potential of dielectric nanofluids can be adjusted using ultrasonication. Figure 9 illustrates how the duration of sonication influences the properties of Therminol-55-based MWCNTs nanofluid [94]. The zeta potential of the nanofluid rises as the duration of sonication extends, reaching an optimal period of ultrasonication. The zeta potential value for the Therminol-55 based nanofluid was |47.7| mV after 30 minutes of sonication and |64.2| mV after 60 minutes of sonication. The findings demonstrate that a 60-minute sonication of Thriminol-55 resulted in an increased absolute value of zeta potential, attributed to the enhanced surface charge of the MWCNTs, which in turn fostered stronger electrostatic repulsion among the MWCNTs. This, in essence, contributes significantly to enhancing the stability of dispersion.

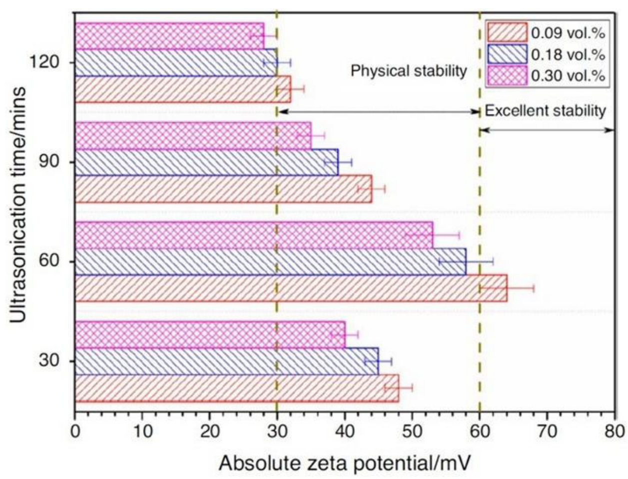

FIGURE 9. Effect of altering sonication time on Zetapotential [94].

3) SURFACE FUNCTIONALIZATION

Surface functionalization tunes nanoparticle surface chemistry to enhance base fluid compatibility and prevent agglomeration. The functional groups (fluorine [32], carboxyl [149], carboxylate [144], [150], hydroxyl [79], [144],

TABLE 4. Influential ultrasonic parameters in dielectric nanofluids across nanomaterial types.

Nanoparticles	Nanomaterial type	Sonication			Ref.
		Method	Probe sonication time	Bath sonication time	
TiO_2 and $ZnFe_2O_4$ doped MWCNTs	Doped	–	–	0.75 h	[144]
F-BNNs	Functionalized	Bath	–	2 h	[32]
graphene + SiO_2, MWCNTs + CeO_2, and ZrO + Al_2O_3	Hybrid	Probe, Bath	0.5 h – 4 h	5 h	[79], [84], [97]
h-BN	2D (non-carbon)	Bath	–	2 h	[81]
TiO_2, Al_2O_3, Co_3O_4, ZnO, FeO_3, Fe_3O_4, Fe_2O_3, CuO, $WO_{2.9}$, $Mn_{0.5}Zn_{0.5}Fe_2O_4$, ZrO_2, and CO_2O_3 CO_2O_3, ZrO_2, $Mn_{0.5}Zn_{0.5}Fe_2O_4$, $WO_{2.9}$, CuO, Fe_2O_3, Fe_3O_4, FeO_3, ZnO, Co_3O_4, Al_2O_3, TiO_2	Metal oxides	Probe, Bath	0.25 h – 6 h	0.5 h – 7 h	[27], [86], [89], [145]
SiC, FeCu, and CdS	Compounds	Probe, Bath	2 h – 4 h	0.75 h – 1.5 h	[37], [83], [98], [99], [146]
Graphene, MWCNTs, CNTs	Carbon	Probe, Bath	2 h	0.5 h – 4 h	[88], [94], [147], [148]

alkyl chains [151], and) are used according to the reviewed studies to attach to the nanoparticles to create better dispersion. The advantages of surface functionalization are enhanced chemical compatibility with transformer oils, decrease of van der Waals forces, in the minimization of aggregation, improved long-term stability of colloidal dispersions without need for surfactant. It all depends on the type of nanoparticles, as different functionalization techniques are used for different nanoparticles. Fluorine functional groups can be attached to h-BN [32]. Carboxyl functional groups can be attached to nanodiamond [149]. Plasma, hydroxyl, alkyl chains functional groups can be attached to silica nanoparticles [79], [151], [152]. Carboxylate functional groups can be attached to silica nanoparticles [79], [151], [152]. Carboxylate functional groups can be attached to TiO_2 nanoparticles [150]. Hydroxyl and carboxyl functional groups can be attached to MWCNTs [144].

Bhunia et al. detailed the functionalization of fluorine on h–BN nanofillers [32]. The nanofluid based on transformer oil demonstrated a stability period of at least one-month post-preparation, during which there was no occurrence of sedimentation or agglomeration. The fluorine-functionalization of the nanosheets resulted in elevated electronegativity, leading to considerable inter-sheet electrostatic repulsion. This was achieved through low filler concentration, which prevented agglomeration and ensured long-term stability. Figure 10 explains the stability of the nanofluid. It shows Tyndall scattering images of the nanofluid (at 0.01 wt.%) just after preparation and after 1 month of preparation. The Tyndall scattering effect indicates that the nanofluid remains stable even after 1 month, without any visible signs of sedimentation or agglomeration.

Shukla and Aiyer have reported the functionalization of nanodiamond surfaces with carboxyl groups (–COOH)

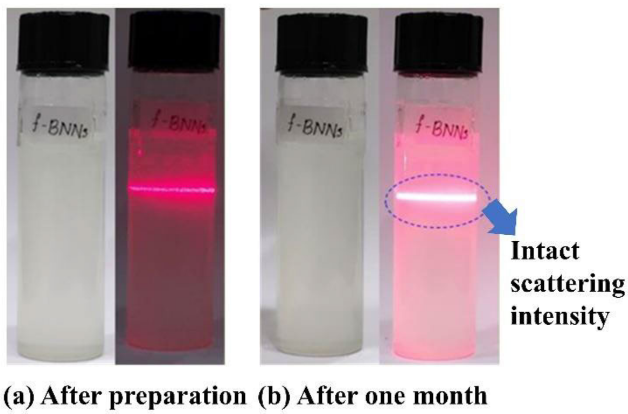

FIGURE 10. Tyndall effect photograph of the nanofluid (0.01 wt.%) immediately after synthesis and following one month of storage [32].

[149]. The nanodiamond-transformer oil suspensions exhibited stability for a minimum of three months, with their stability verified by UV-visible spectrometry measurements. The study indicates that homogeneously dispersed nanodiamonds (up to 0.12% concentration) in transformer oil exhibited stable absorbance values for up to 960 hours, thereby confirming the stability of nanofluids at this concentration. Walvekar et al. employed a surface functionalization technique to synthesize hybrid SiO_2–graphene nanoparticles utilizing the sol–gel method [79]. Figure 11 shows FTIR spectral profiles of pure graphene and SiO2-functionalized graphene nanoparticles. The existence of –OH (hydroxyl) groups, indicated by a weak peak around 3500 cm ^{1}, suggests a minor presence of these groups, which acted as reactive sites for silica deposition during the sol–gel process. The graphene surface was effectively functionalized via the formation of Si–O–C (approximately 1594–1605 cm ^{1}) and

Si–O–Si (approximately 1080–1090 cm ^{1}) bonds, as verified by FTIR analysis. This surface coating significantly modified the surface chemistry of graphene, resulting in improved dispersion and stability of the nanoparticles in transformer oil.

Zakaria et al. states that the surface of the silica nanoparticles was functionalized using atmospheric pressure plasma discharge [152]. This plasma treatment was done to enhance the interfacial interaction between the nanoparticles and the base mineral oil, in order to improve the sedimentation issue that is commonly observed in nanofluids. Pourpasha et al. applied surface functionalizing technique [144]. First treated with nitric acid, the MWCNTs underwent magnetic stirring and ultrasonication. Oxygen-containing functional groups—like carboxyl and hydroxyl groups—were added to the surface of MWCNTs by this method, so increasing their chemical reactivity. TiO_2 nanoparticles were then doped into functionalized MWCNTs. This increased the thermal stability and dispersibility of transformer oil nanoparticles. Better temporal stability led to the selection of this approach over surfactant-based physical modification.

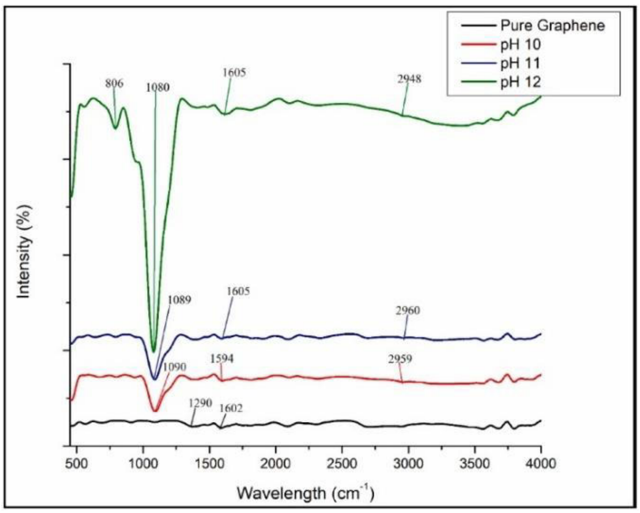

FIGURE 11. FTIR spectral profiles of pure graphene and SiO_2-functionalized graphene nanoparticles [79].

Lv et al. the TiO_2 nanoparticles were functionalized using oleic acid [150]. The FT-IR spectrum shows that the carboxylate (-COO-) group from oleic acid is covalently bonded with the titanium sites on the nanoparticle surface, mainly through bidentate linkages. This indicates that the TiO_2 nanoparticles were well functionalized with oleic acid. The enhancement of TiO_2 nanoparticle dispersion in mineral oil can be achieved by optimizing the application of modifying agents to functionalize the nanoparticles. Dan et al. used hydrophobic alkyl chains as surface modifiers grafted onto SiO2 nanoparticles [151]. Figure 12 shows molecular simulation models of SiO_2 nanoparticles with increasing surface modification. Figure 12a shows unmodified nanoparticles, hydrophilic, prone to aggregation. Figure 12b–d shows nanoparticles modified with short to long alkyl chains ($–(CH_2)_3CH_3$ to $–(CH_2)_9CH_3$), making the surface more hydrophobic and enhancing dispersion stability in natural esters. The functional groups are propyl group ($–(CH_2)_3CH_3$), hexyl group ($–(CH_2)_6CH_3$), and nonyl group ($–(CH_2)_9CH_3$). These groups were grafted onto the SiO_2 nanoparticle surface to reduce Coulombic interactions, enhance van der Waals interactions with the base fluid, and improve dispersion if SiO_2 nanoparticles in non-polar natural ester insulating fluid.

C. LONG-TERM STABILITY AND AGING EFFECTS

Stability over an extended time period is an important performance factor for nanofluids application in industry [153], especially when used in transformer cooling and insulation system [154]. Settling or agglomeration of the nanoparticles over long time is the challenge related to the stability of the nanofluids. Reviewed studies show that with time nanoparticles cluster due to van der Waals forces lose this uniformity, then gravitational settling that eventually leads to particles falling to the bottom of storage containers or transformer tanks. This can change the dielectric and thermal properties of the fluid [31]. As discussed earlier various techniques can be used for mitigating such effects including surfactants, surface functionalization, and ultrasonication.

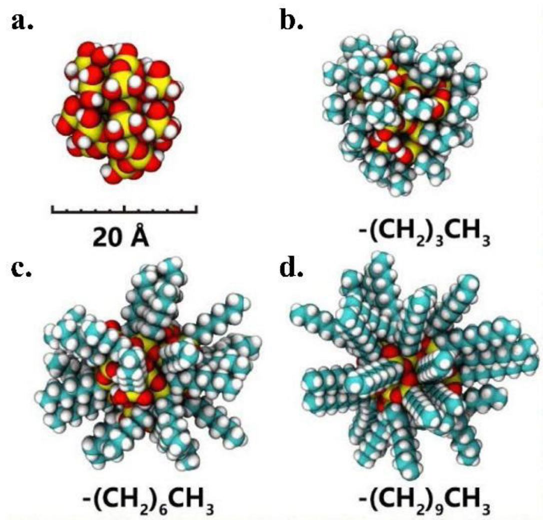

FIGURE 12. FTIR spectral profiles of pure graphene and SiO_2-functionalized graphene nanoparticles [151].

Table 5 indicates that studies attained enduring stability from a minimum duration of few days to seven years. The nanofluid containing 8.7 nm Fe_3O_4 nanoparticles in Mogul Trafo CZ–A oil, stabilized with oleic acid, exhibited the longest stability duration of up to seven years [155]. This signifies an extraordinarily robust interaction between the particle type and the surfactant-base fluid combination. Moreover, carbon-based nanomaterials, including graphene and nanodiamonds, exhibit superior long-term stability [103], [149]. Graphene dispersed in transformer oil (0.1 wt%) remained stable for three months without the need for a surfactant,

TABLE 5. Time stability of dielectric nanofluids.

Base fluid	Nanoparticle	Concentration	Size (nm)	Preparation method	Surfactant	Sonication		Stability period	Ref.
						Type	Time		
Natural ester liquid	h–BN	0.03 g/L	–	2-step	–	Bath	1.5 h	45 days	[14]
Natural ester liquid	h–BN	0.03 g/L	–	2-step	APTES	Bath	1.5 h	45 days	[14]
Transformer oil	MWCNT-OH	0.001 wt%	10–20	2-step	Stearic acid	Bath	6 h	40 days	[160]
Transformer oil	TiO_2–doped MWCNT	0.2 wt%	42–60	2-step	Oleic acid	Bath	1 h	16 days	[158]
Mineral oil–1	TiO_2 (Anatase)	0.005 wt%	50–70	2-step	–	Bath	2 h	3 months	[85]
Mineral oil–2	TiO_2 (Anatase)	0.005 wt%	50–70	2-step	–	Bath	2 h	3 months	[85]
T66	TiO_2 (Anatase)	–	5.9	1-step	Stearic acid	Bath	30 min	56 days	[161]
Mineral oil	Fe_3O_4–doped MWCNT	–	–	1-step	–	–	8 h	26 days	[159]
Transformer oil	CeO_2	–	3–7	1-step	Oleic acid	–	10 min	5 months	[157]
Coconut oil (Dry)	ZnO	1 wt%	30–50	2-step	–	Probe	1 h	1 week	[68]
Coconut oil (Wet)	ZnO	0.05 wt%	30–50	2-step	Oleic acid	Probe	1 h	1 week	[68]
Dry MIDEL eN1215	ZnO	1 wt%	30–50	2-step	–	Probe	1 h	1 week	[68]
Wet MIDEL eN1215	ZnO	0.04 wt%	30–50	2-step	Oleic acid	Probe	1 h	1 week	[68]
Transformer oil	h-BN	0.05 wt%	<450	2-step	–	Bath	2 h	1 week	[81]
Mineral	Al_2O_3	0.02 wt%	60	2-step	Oleic acid	–	–	1 day	[100]
Natural ester liquid	Al_2O_3	0.02 wt%	60	2-step	Oleic acid	–	–	1 day	[100]
Mineral oil	ZnO & TiO_2	0.01 wt%	18 & 18	2-step	–	–	2 h	7 days	[162]
Mineral oil	TiO_2 (Anatase)	0.7 g/L	9.5 - 16.6	2-step	–	Probe	15 min	1 month	[27]
Mineral oil-1	BNNs- Fluorinated	0.005 wt%	5	2-step	–	Bath	2 h	1 month	[32]
Mineral oil-2	BNNs- Fluorinated	0.01 wt%	5	2-step	–	Bath	2 h	1 month	[32]
Transformer oil	Graphene	0.1 wt%	12	2-step	–	Bath	4 h	3 months	[156]
Mogul Trafo CZ-A	Fe_3O_4	0.48 vol%	8.7	2-step	Oleic acid	–	–	7 years	[155]
Natural ester liquid	SiO_2 & WO_3	0.2–1 wt%	18, 40	2-step	Oleic acid	–	–	2 days	[163]
Cottonseed oil	Graphene	0.01 wt%	3-6	2-step	SDBS	Probe	0.5&1 h	90 days	[103]
Mineral oil	Nanodiamonds	0.12 wt%	4–8	2-step	Oleic acid	Both	1&0.5 h	3 months	[149]

partly due to prolonged bath sonication (4 hours) [156]. Oleic acid-stabilized nanodiamonds in mineral oil exhibited consistent stability, remaining dispersed for three months under a combination of conventional and ultrasonication methods [149]. A notable example is a graphene–cottonseed oil suspension that exhibited 90 days of stability at a low concentration (0.01 wt%), utilizing SDBS surfactant in conjunction with probe sonication [103].

Nanofluids composed of metal oxides are widely recognized for their exceptional dielectric and thermal characteristics, especially those containing TiO_2 [85], ZnO [68], Al_2O_3 [100], CeO_2 [157], and Fe_3O_4 [155]. The long-term stability of these nanoparticles varies significantly depending on the methods used for their preparation. Anatase TiO_2 demonstrated remarkable stability in mineral oil for a duration of three months, even with sonication and the absence of surfactants [85]. In transformer oil with a reduced sonication duration, the oleic acid-modified CeO_2 demonstrated stability for five months. ZnO-based fluids exhibited stability for a limited duration (approximately one week) in a dispersion devoid of surfactants (with the exception of sonication via probe) [157]. Significantly, oleic acid-stabilized Fe_3O_4 nanoparticles demonstrated an impressive 7-year stability in Mogul Trafo CZ-A oil, highlighting the exceptional potential of surface-functionalized magnetic oxides in ultra-long-term insulating fluids [155].

Nanoparticles have been doped and fluorinated for better dispersion and performance in dielectric nanofluid. The doping of TiO_2 in MWCNTs, with loading 0.2 wt% using oleic acid and 1-hour bath sonication, led to improved stability up to 16 days in transformer oil [158]. Fluorinated BNNs exhibited stability in mineral oil for one month, provided they underwent 2 hours of bath sonication at concentrations ranging from 0.005 to 0.01 wt% of fluorinated-BNNs in the same mineral oil, without the use of surfactants [32]. Doping and fluorination, in conjunction with uniform dispersion, can enhance dielectric properties and thermal conductivity [32], [158], [159].

Transformer oils are the base fluids for dielectric nanofluids and are prone to chemical degradation as well as oxidation in long-term operation [164], [165]. Literature review shows that decomposition byproducts, including acids and sludge [166], are produced from exposure to high temperature, oxygen, and electrical stress. The resulting byproducts can change the surface chemistry of nanoparticles, which in turn can influence dispersion stability. According to a few reports, functionalized nanoparticles are apparently more resistant to oxidative degradation [167], which could increase long-term stability. Changes in nanoparticle dispersion and chemical decomposition could cause nanofluids to change in breakdown strength, thermal conductivity, and viscosity [8]. Poorly stabilized nanofluids suffer from poor dielectric performance due to conductive pathways caused by nanoparticle clustering, according to the reviewed studies. Ageing nanofluids can affect their thermal properties, including reduced heat transfer due to nanoparticle settling over time. Some recommend regular checks and re-dispersion methods to maintain intended performance over time.

IV. DIELECTRIC, THERMOPHYSICAL, CHEMICAL PROPERTIES OF NANOFLUID

This section outlines the review of essential properties of dielectric nanofluids, categorized into three categories: dielectric properties, thermophysical properties, and chemical properties, as shown in Figure 13. The dielectric properties pertain to the electrical stress of the nanofluid [154], specifically the breakdown voltage (including AC and impulse), partial discharge, and dissipation factor, reliable insulation of high-voltage applications. The thermophysical properties, including thermal conductivity, viscosity, flash point, pour point, and fire point, significantly influence the nanofluid's behavior under temperature variations, thereby affecting heat dissipation, flow efficiency, and reliability [2]. Ultimately, the chemical property of acidity is of paramount importance [154]. Prolonged exposure to excessive acidity will result in equipment corrosion and deterioration. The combination of these properties ensures the nanofluid's performance, safety, and durability in any electrical system, especially in power transformers.

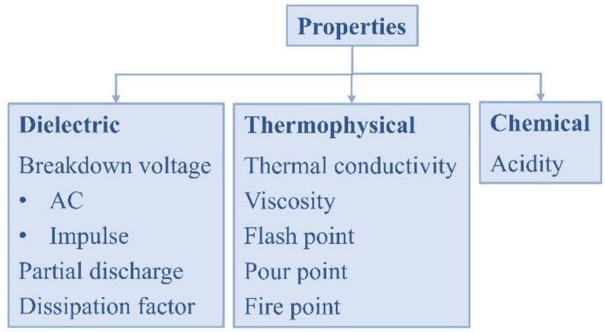

FIGURE 13. Properties of dielectric nanofluids.

A. BREAKDOWN VOLTAGE

The breakdown voltage employed for insulation testing can be categorized into AC, DC, and impulse types [168]. The AC breakdown voltage of dielectric nanofluids is a vital measure of insulation characteristics. AC breakdown voltage was commonly measured in accordance with IEC 60156 and ASTM D1816 standards [1], [169]. Studies demonstrate that nanoparticles in base fluids act as electron scavengers [85], capturing free electrons, delaying the breakdown process, and improving breakdown voltage. An average enhancement of approximately 21% in AC breakdown voltage has been reported in the literature [1]. Minimizing nanoparticle sizes increases surface area and enhances electron trapping efficacy at optimal concentrations [112]. Figures 14a and b illustrate the AC breakdown voltage of nanofluids at different concentrations, measured for 13 nm and 50 nm Al_2O_3 nanoparticles [112]. This clearly indicated that nanofluids containing smaller nanoparticles surpassed those with larger nanoparticles. At an optimal concentration of 0.2 g/L, 13 nm nanoparticles exhibited a breakdown voltage of 79.87 kV, whereas 50 nm nanoparticles demonstrated a breakdown voltage of 74.3 kV. Excessive loading of nanoparticles led to agglomeration, thereby reducing the discharge path length and diminishing the dielectric breakdown voltage [31]. Furthermore, temperature exerts a positive influence on the BDV, as an increase in temperature correlates with an enhancement in BDV [170], [171]. Nonetheless, this effect diminishes at elevated temperatures [171]. Nanoparticles with enhanced conductivity (such as Fe_3O_4), outperform insulating nanoparticles (such as SiO_2 and Al_2O_3), in dielectric nanofluids employing mineral oil as base fluid [1]. This may result from the elevated BDV of mineral oil in comparison to natural ester liquids. Surfactants and sonication augment the stability of dispersions and prevent agglomeration, thereby enhancing the AC breakdown voltage of dielectric nanofluids. Furthermore, surfactants generate an interfacial zone that facilitates electron trapping, thereby enhancing breakdown voltage.

Impulse breakdown voltage tests measures how insulation reacts to a rapid, intense surge of voltage (Viz., lightning strikes). Impulse breakdown voltage was commonly measured in accordance with IEC 60897 and ASTM D3300 standards [5], [136]. The nanoparticles disrupt the electric field distribution of pure oil, characterized by homogeneous

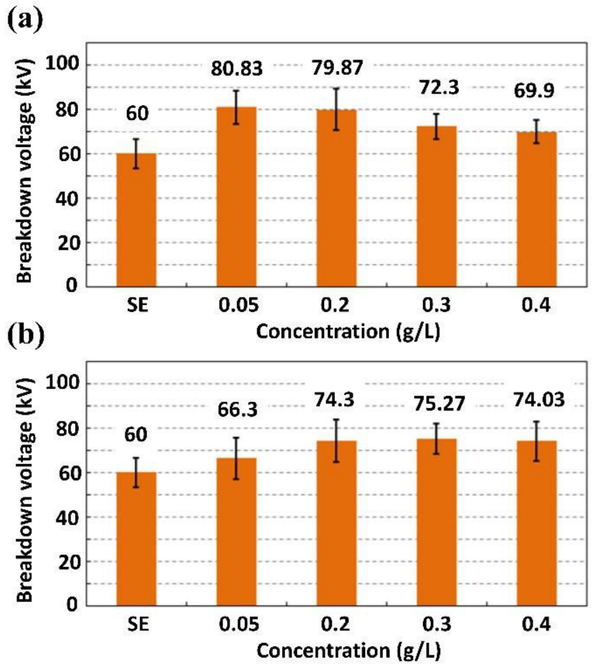

FIGURE 14. AC breakdown voltage of nanofluids at different concentrations measured for (a) 13 nm and (b) 50 nm Al_2O_3 nanoparticles [112].

polarization, and capture fast electrons through surface polarization, ultimately hindering the propagation of streamers [170]. Uniformly distributed nanoparticles in base fluid create branched discharge pathways that enhance breakdown resistance [133]. However, the pathways for charge are concentrated due to agglomeration and sedimentation, leading to a decrease in BDV. The breakdown voltage exhibits variations depending on the polarity of the applied voltage. Studies indicates that negative polarity impulses generally produce a greater breakdown voltage than positive ones in both base oil and nanofluids [172]. Consequently, the positive impulse serves as a more critical element for the insulation system. Enhancing positive impulse breakdown voltage levels can be achieved by dispersing nanoparticles in a base oil. Nonetheless, the disparity in positive and negative impulse BDV levels is smaller in nanofluids compared to pure oils. Moreover, smaller nanoparticles (Example, Lv et al. reported nanoparticle size ~20 nm [173]), using certain surfactants at optimal levels [59], and optimal nanoparticle concentration improve the performance while very large concentration has a detrimental effect.

The improved dielectric nanofluids' breakdown performance is attributed to several important mechanisms that may play a significant role in changing electron dynamics and electric field distribution [132], [174]. In the presence of applied electric field, instantly these polarized nanoparticles dispersed in the insulating fluid create localized regions of permittivity and conductivity difference [175]. Such polarization causes nanoparticles to behave as electron scavengers, reducing the drift velocity of free electrons by trapping them [176]. Nanoparticles stop these charge carriers and thus slow down the formation of conductive pathways leading to an increased breakdown voltage. This trapping effect is intensified in the case of smaller nanoparticles, as they have a much higher surface area-to-volume ratio, making them more effective in enhancing dielectric strength than larger particles [53].

Another key mechanism is related to changing the distribution of the electric field. In pure oil, the field is uniform and allows electrons to accelerate and start a breakdown process much easier. The presence of nanoparticles breaks this uniformity, scattering the electric field lines and causing the electrons to encounter a more convoluted path [1]. Branching these effects mitigate energy transfer thus reducing the probability of a focused discharge. Thus, nanoparticles affect pre-breakdown streamer propagation by increasing the number of streamer branches, while simultaneously decreasing their thickness and velocity. The slow, more fragmented streamers take higher voltage to lead to total breakdown, giving an added boost to the insulation strength.

Nevertheless, these positive effects are strongly dependent on the stability of nanoparticle dispersion. As a result of high concentration or poor stabilization, nanoparticles agglomerate to larger clusters which form conductive bridges, thereby shorten the discharge paths and decrease the breakdown voltage [1]. Sedimentation of agglomerated particles further exacerbates this issue by creating localized regions of high electric stress. Thus, appropriate sonication [31], surfactants [30], and surface functionalization [149] are valuable in maintaining the uniform dispersion of the nanoparticles, where incorporation of nanoparticles form effective traps without any aggregation or sedimentation.

Figure 15 shows the average AC breakdown voltage of mineral oil-based carbon nanotube (CNT) nanofluids at 30 and 120 minutes of sonication periods [53]. The AC BDV of the CNT nanofluids was higher when subjected to 120 minutes of sonication, compared to 30 minutes of sonication, across all three CNT nanofluid concentrations (0.01 g/L, 0.03 g/L, and 0.05 g/L). The longer sonication time of 120 minutes improved the AC BDV by 8.80%, 25.14%, and 11.80% for the 0.01 g/L, 0.03 g/L, and 0.05 g/L CNT nanofluid concentrations, respectively, compared to the shorter 30-minute sonication period. This indicates that the longer ultrasonication time of 120 minutes resulted in a more homogeneous and well-dispersed distribution of CNTs in the mineral oil, without any aggregation, leading to the enhanced AC breakdown voltage performance of the nanofluids.

The nanoparticle type is also very important. However, conductive nanoparticles are more effective for electron-trapping owing to their high conductivity while insulating nanoparticles modify the electric field [170], [177]. However, in certain conditions, hybrid nanofluids (i.e., containing more than one type of nanoparticles) may synergistically enhance the breakdown performance by incorporating both types of enhancement mechanisms [178], thus, leading to a better breakdown performance. In addition, these mechanisms are impacted by external factors, including

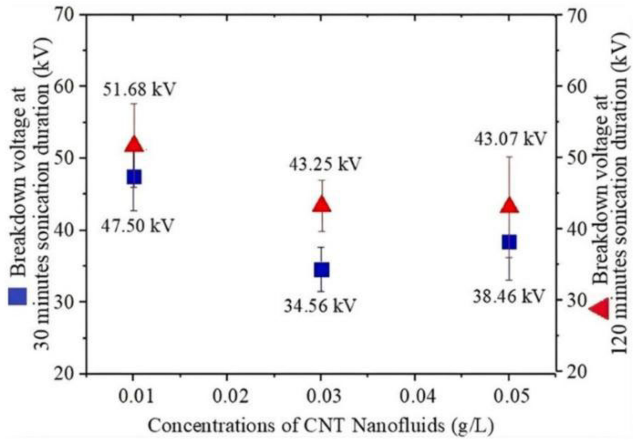

FIGURE 15. AC breakdown voltage of CNT-enhanced mineral oil nanofluids after sonication durations of 30 and 120 minutes [53].

temperature and magnetic fields—temperature will typically increase the breakdown strength due to lower viscosity and greater particle mobility [170], [171]; using magnetic fields can align the conductive nanoparticles thereby enhancing their capacity to entrap electrons [179].

B. PARTIAL DISCHARGE

Evaluating partial discharge is essential for safeguarding the performance and integrity of electrical systems [180]. One of the top causes of localized long-term degradation of electrical insulation is partial discharge in areas with contaminants or electric field inhomogeneities (such as water, air bubbles, particles) [181]. Studies revealed that the partial discharge in nanofluids grows slower than that in base oils [182], [183]. Partial discharge measurements were commonly conducted in accordance with the IEC 60270 standard [38]. Kurimsky et al. through electrical and acoustic measurements, studied partial discharge in nanofluids, showing that nanofluids has a much higher magnitude and counts of partial discharge pulses compared to the nanofluids (Figure 16) [183]. In addition, at higher applied voltages, the suppression effect on partial discharge was found to be more intense for the nanoparticles [183]. A similar trend has been observed in aged samples. Sun et al. subjected pure oil and nanofluids to accelerated aging and found that while partial discharge inception voltage decreased with aging in both fluids, nanofluids consistently maintained higher partial discharge inception voltage levels [184]. Other studies reported reduced streamer repetition rates and shorter discharge paths in nanofluids compared to pure oil [126]. Notably, nanofluids exhibited dramatically lower pulse counts, cumulative discharge (nC), and maximum discharge current (nA)—approximately 10% of those in pure oil [185]. Furthermore, research on nanofluid-impregnated pressboard insulation revealed improved PDIV, along with enhanced AC and DC breakdown strength, compared to conventional mineral oil-impregnated insulation [1]. Since transformer lifespan depends more on cellulose insulation than on the oil itself, the beneficial effects of nanoparticles on cellulose's electrical properties are particularly significant [122].

C. DISSIPATION FACTOR

A high-quality insulating liquid is anticipated to exhibit a minimal dissipation factor (tanδ) value [58], [136]. Dissipation factor measurements were commonly performed in accordance with IEC 60247 and ASTM D924 standards [57]. While tanδ tends to decrease with aging (deterioration) and higher frequencies, it generally increases with rising temperature [186]. However, research on the effects of nanoparticle addition to pure oil presents conflicting findings regarding tanδ behavior. Most studies indicate that nanofluids exhibit lower tanδ values than pure oil, even after aging [187]. Nevertheless, the concentration of nanoparticles plays a crucial role in determining this trend [58], [106], [136]. A recent study observed that beyond a certain nanoparticle concentration, the decreasing tanδ curve reverses and begins to rise [188]. This finding was supported by another study, which demonstrated that tanδ decreases up to a graphene concentration of 0.0025 wt% at different measured temperatures but increases again at higher concentrations, as illustrated in Figure 17 [188]. The inverse relationship between volumetric resistivity and tanδ further explains this phenomenon [31]. Nanofluids based on natural esters have higher inherent values of tanδ due to the characteristics of the base fluid, although the presence of the nanoparticle reduces the tanδ value [136].

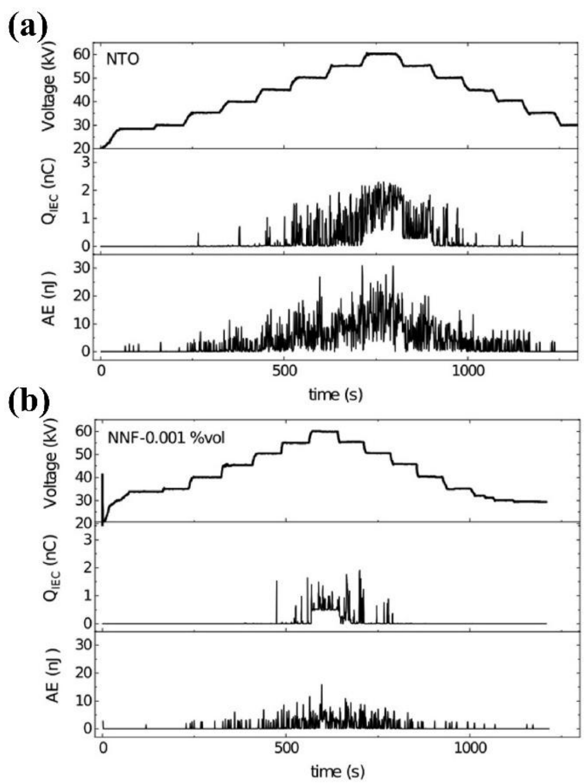

FIGURE 16. Partial discharge behavior in (a) naphthenic transformer oil and (b) nanofluid shown through apparent charge (QIEC) and acoustic emission (AE) at multiple applied voltages [183].

D. THERMAL CONDUCTIVITY

Thermal conductivity was commonly measured in accordance with ASTM D7896 [113]. Many studies have reported that the thermal conductivities of the nanofluids are greater than that of pure oils [70], [103], [149]. Table 6 displays thermal conductivity enhancement in dielectric nanofluids as a percentage. Since nanoparticles have high thermal conductivities by nature, the addition of nanoparticles in oil will improve the thermal characteristics of the corresponding nanofluid. Extensive studies show that nanoparticles can enhance the thermal conductivity in wide range of base oils [14], [70], [127], [128], [129], [189]. Nevertheless, this improvement is not necessarily reflected proportionally in heat transfer rates across hot and cold spots [1]. However, in power transformer applications, nanofluids have higher thermal conductivity than pure oils, but the reduction in hotspot temperatures under steady-state conditions may only be a few degrees [1]. This limited improvement can be attributed to the increased fluid viscosity caused by nanoparticle addition. Even a slight temperature increase is critical for transformers, as every ~7°C rise in temperature reduces their operational lifespan [190]. The advantages of nanoparticles become more apparent in larger transformers, where localized temperature gradients are more severe, emphasizing the need for additional field validation.

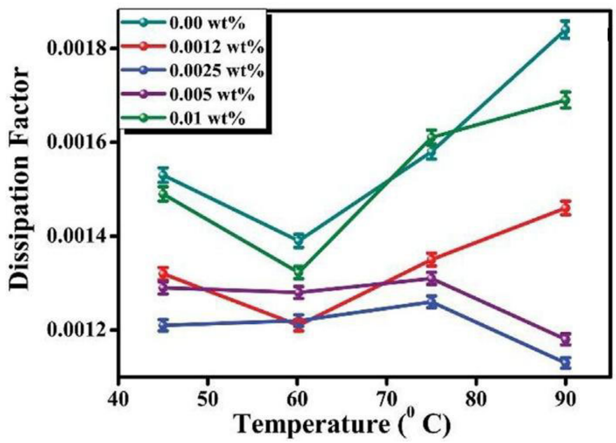

FIGURE 17. Variation in dissipation factor with nanofluid concentration [188].

The thermal conductivity increases linearly with nanoparticle volume fraction at low concentrations. However, at high concentration, this trend is reversed because clustering nanoparticles decrease effective heat transfer area available [149], [191]. This effect can be mitigated by using surfactants that can provide better stabilization of the dispersion. In addition, small nanoparticles have higher thermal properties compared to larger nanoparticles with same mass concentration due to their size and higher surface-area-to-volume ratio [31]. Like mineral oils, synthetic and natural esters also experience improved thermal conductivity with nanoparticle addition. However, their heat dissipation capability is not necessarily superior to mineral oils, as the base fluid's viscosity remains the dominant factor in overall thermal performance.

E. VISCOSITY

The viscosity parameter holds significant importance for all cooling fluids [196], [197]. Viscosity measurements were commonly conducted in accordance with ASTM D88, ASTM D445, and ASTM D2161 standards, while IEC 60296 was referred to for viscosity specifications of transformer oil [198]. Fluids with low viscosity can enhance equipment performance and prolong the operational lifespan of the transformer [2], [199]. In power transformers, fluids facilitate heat transfer primarily through convection and conduction, where viscosity plays a crucial role in enhancing convective heat transfer efficiency, therefore, be minimized to the lowest possible value [6]. The findings exhibit inconsistencies; however, they predominantly indicate that nanofluids possess greater viscosity compared to base oils [200]. Generally, the density and viscosity of the nanofluid increase with the incorporation of nanoparticles, this would impede the heat transfer. Nonetheless, the characteristics of nanoparticles contribute to the improvement of thermal conductivity in nanofluids [43], partially mitigating the negative impacts of viscosity factors.

At elevated temperatures, both base oils and nanofluids demonstrate a decrease in viscosity [79], [201]. In heat-generating systems like transformers, the heat produced during operation roughly offsets the viscosity increase induced by the nanoparticles. Surfactants may diminish nanofluid viscosity by disrupting the interactions among nanoparticles and enhancing shear rates [54], [69], [202]. AlN (0.5 wt%) nanoparticles dispersed in base oil demonstrated a significant decrease in dynamic viscosity when oleic acid was used as a surfactant (Figure 18) [203]. The dispersion effect of surfactant certainly increases the surface area of the nanoparticles, which in turn enhances thermal conductivity [145]. Previous studies have examined viscosity changes for various base fluids and nanoparticle suspensions. Natural esters are being increasingly examined although they have a viscosity that is much higher than that of mineral oils [204], [205]. Although addition of nanoparticles leads to a higher viscosity in natural ester-based nanofluids [206], the actual increase is higher than in mineral oil-based nanofluids. The same trend also applies for high-viscosity synthetic esters, which also confirms the increase in viscosity with increasing concentration of the nanoparticles.

F. FLASH, POUR, AND FIRE POINT

Studies confirm that modification occurs in essential physicochemical characteristics of insulating oils as the nanoparticles affect flash [207], [208], fire [207], [208], and pour point [208]. Flash, pour, and fire point measurements were commonly conducted in accordance with ASTM D97 and ASTM D92, while IEC 60296 was referred to for the

TABLE 6. Thermal conductivity enhancement in dielectric nanofluids expressed as a percentage.

Base fluid	Nanoparticle	Concentration	Size (nm)	Surfactant	Sonication type	Sonication Time	Thermal conductivity Enh. (%)	Ref.
Mineral oil	Nanodiamonds	0.12 wt%	4–8	Oleic acid	Both	1&0.5 h	14.5	[149]
Graphene	Graphene	0.01 wt%	3-6	SDBS	Probe	0.5&1 h	29,47 time	[103]
Palm oil Coconut oil Soybean oil	Hybrid TiO_2-Al_2O_3	0.2 wt.%	<21	CTAB	Bath	3 h	48.9 15.8 11.4	[70]
Transformer oil	ZrO_2	0.2 g/L	5-10	CTAB	–	30 min	16.6	[72]
Transformer oil	Graphene	0.1 wt%	12	–	Bath	4 h	≈ 14	[156]
TRANSOL	Graphene sheets	0.0025 wt%	50–70	–	Probe	2 h	30	[188]
Transformer oil	Graphene quantum dots	0.001 wt%	5–17	–	Probe	30 min	3.4	[192]
Mineral oil	BNNs- fluorinated	0.005 wt%	5	–	Bath	2 h	0.9	[32]
Transformer oil	AlN & Al_2O_3	0.5 vol%	13&50	Oleic acid	Bath	–	8 & 20	[193]
Natural ester liquid	Al_2O_3	0.02 wt%	60	Oleic acid	–	–	10.7	[100]
Mineral oil	Al_2O_3	0.02 wt%	60	Oleic acid	–	–	9.1	[100]
Transformer oil	h-BN	0.05 wt%	<450	–	Bath	2 h	17	[81]
Transformer oil	CeO_2	–	3–7	Oleic acid	–	10 min	14.6	[157]
Mineral oil	Fe_3O_4 doped MWCNT	–	–	–	–	8 h	50	[159]
T66	Anatase TiO_2	–	5.9	Stearic acid	Bath	30 min	44.6	[161]
Transformer oil	Ag-WO_3 composite	High	35–55	–	–	–	41	[194]
Mineral oil	TiO_2- Anatase	0.005 wt%	50–70	–	Bath	2 h	48.5	[85]
Mineral oil	TiO_2- Anatase	0.005 wt%	50–70	–	Bath	2 h	210	[85]
Transformer oil	TiO_2–doped MWCNTs	0.2 wt%	42–60	Oleic acid	Bath	1 h	8.6	[158]
Transformer oil	MWCNT-OH	0.001 wt%	10–20	Stearic acid	Bath	6 h	15.59	[160]
Transformer oil	MWCNT	0.001 wt%	10-20	Oleic acid	Bath	6 h	14.48	[160]
Mineral oil	Al_2O_3	2 wt%	30	–	–	–	20.29	[189]
Mineral oil	CuO	2 wt%	30	–	–	–	24.46	[189]
Mineral oil	Fe_3O_4	2 wt%	30	–	–	–	15.87	[189]
Nitro libra	Iron oxide	–	23	–	Probe	20 min	4.51	[195]
Natural ester liquid	h–BN	0.03 g/L	–	APTES	Bath	1.5 h	20.33	[14]
Natural ester liquid	h–BN	0.03 g/L	–	–	Bath	1.5 h	12.68	[14]

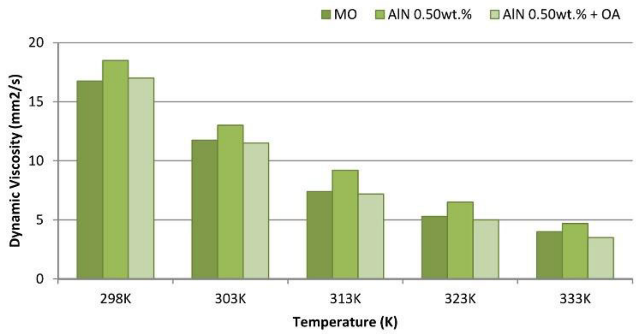

FIGURE 18. Dynamic viscosity was evaluated for pure mineral oil, 0.50 wt.% AlN nanofluid, and oleic acid-modified 0.50 wt.% AlN nanofluid across a range of temperatures [1], [203].

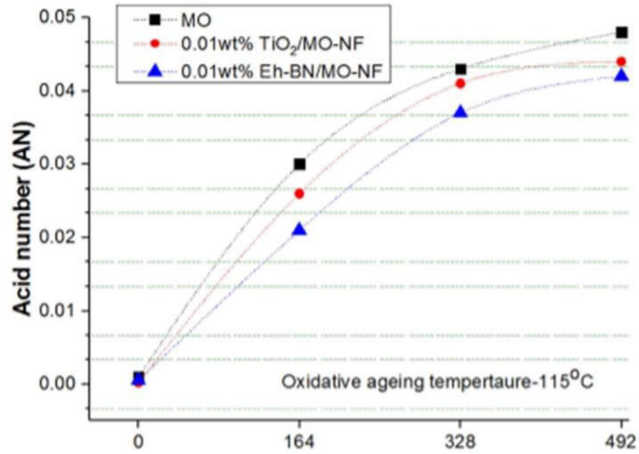

FIGURE 19. Variation of acid value over the ageing period [213].

specification limits of these properties [198]. The low flash point is crucial, since the formation of flammable gas due to localized heating or overloading might result in permanent faults [209]. Nanofluids were consistently reported to have higher flash points compared to the base fluids. Evidently, the addition of ZnO, TiO_2, and Al_2O_3 nanoparticles suspended in mineral oil were found to increase flash points, with ZnO nanoparticles providing the greatest enhancement (i.e., 23.93%) [106]. Another study observed flash point enhancements of up to ~40% [210], with similar trends across different nanoparticle types and base fluids. On the contrary, pour point, not very important for operational transformers due of its significance in cold areas, is not significantly influenced by nanoparticles and does not confer clear benefits over pure oils [106], [107]. Although most research identifies flash point, fewer studies focused on fire and pour points [207], [208]; the changes in fire and pour points are not expected to be proportional to the concentration of nanoparticles and may vary randomly with additive levels.

G. ACIDITY

The term acidity concerns the quantity of organic and inorganic acids found in the oil as the milligrams of potassium hydroxide (KOH) necessary for neutralizing the free acids in 1 gram of oil. Acidity is generally measured according to ASTM D974, ASTM D664, and IEC 62021 standards in transformer oil [198], [211]. Transformer oil mainly contains acids derived from oil degradation and oxidation byproducts. Acids can also be introduced from outside, specifically from atmospheric pollutants. These organic acids break down the insulation structure, can cause corrosion within the transformer. Ideally, pure transformer oil should not contain acid, but in practice, trace amounts are often present. S. Sumathi et al. compared the acidity of prepared nanofluids with base transformer oil [212]. The incorporation of Al_2O_3, TiO_2, and MoS_2 nanoparticles reduced the acid content of nanofluids compared to the base transformer oil, which helps to mitigate the transformer corrosion risk. Moreover, acidity usually rises with age. M. Maharana et al. measured and compared the acid number of prepared nanofluids over 492 hours with conventional transformer oil [213]. The nanofluids containing both Eh-BN and TiO_2 NPs retained lower acidity than the transformer oil throughout the aging period (Figure 19). This is attributed to the fact that moisture in the oil accelerates the aging process, contributing to the generation of acidic compounds. The nanoparticles in nanofluids help mitigate this effect by adsorbing moisture [68], which in turn suppresses acid formation during aging.

V. CONCLUSION

This review presents dielectric nanofluids' dielectric, thermophysical, and chemical properties. The review discusses various aspects including base fluids, nanoparticles, surfactants, stabilization methods, factors affecting stability, methods to enhance stability, long term stability, and nanoparticle effect on aging. Nanoparticle size, agglomeration control and zeta potential directly control the stability of dielectric nanofluids. Strategies, such as the use of surfactants, the application of ultrasonication, and the functionalization of nanomaterials can avoid agglomeration ensure their considerable stability in suspension. Oleic acid, CTAB, and SDBS are popular among the efficient surfactants. Sonication type (probe/bath) as well as the optimized sonication time, are dependent upon type and concentration of nanoparticles. Fluorination and carboxylation enhance long-term stability. Fe_3O_4 (7 year) and CeO_2 (5 months) nanofluids demonstrated excellent long-term stability. For industrial applications, periodic stability checks are required due to aging effects.

Studies on dielectric nanofluids mostly focused on electrical insulation and thermal performance. Nanofluids outperform traditional insulating base oils in dielectric performance. A well-known test, AC breakdown voltage test shows that nanofluids have greater breakdown strength than pure base fluids, with an average enhancement of approximately 21%. Positive lightning impulse breakdown voltage (LI-BDV) testing demonstrates that nanofluids outperform base fluids. Nanoparticle size at optimal concentration are also important considerations; studies show that smaller nanoparticles perform better in terms of dielectric strength. This is due to larger surface area of nanoparticles. While nanoparticle loading beyond optimal concentration can reduce the dielectric breakdown strength. Nanoparticles slow breakdown and inhibit streamer progression, resulting in improved breakdown strength. Nanofluids have higher partial discharge inception voltage (PDIV), which leads to less and slower partial discharges than pure oils. Studies show that nanofluids have lower tanδ values than pure oil; this impact is very dependent on nanoparticle concentration, so stressing the importance of ideal loading to reduce tan δ.

The characteristics of the base fluid play a crucial role in determining the effectiveness of nanoparticles, mineral oil typically showing superior performance compared to those made from vegetable oils because of low viscosity. While nanoparticle suspension increases fluid viscosity.

Minimum concentration, surfactants, and temperature adjustments can mitigate this effect. Another advantage of dielectric nanofluids is improved thermal conductivity, which aids heat dissipation in applications such as oil-filled transformers. Nanofluids also exhibit higher flash points and decelerate cellulose insulation degradation. Additionally, nanoparticles help neutralize acidity in transformer oils, reducing corrosion risks and prolonging operational lifespan.

Despite these advantages, there are inconsistencies in research findings, even among similar nanoparticles and base fluids, due to differences in particle size, stabilization methods, and measurement techniques. Developing reliable nanofluids for transformers requires multivariate analysis and standardized preparation and testing protocols. Although theoretical and lab-based results are promising, long-term field studies are essential to evaluate aging effects, magnetic field interactions, thermal efficiency, stability in dielectric performance, and sustained nanoparticle dispersion over a period before widespread industrial adoption.

VI. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

A. CHALLENGES

- Stability of dielectric nanofluids: Nanoparticles commonly exhibit a tendency to agglomerate and sediment as a result of Van der Waals attractive forces. This diminishes thermal and dielectric efficiency. Enhancements can be achieved through the use of surfactants, ultrasonication, and surface functionalization. The long-term stability is essential for real-world applications, yet it continues to pose a significant challenge.
- Dielectric nanofluid viscosity: Higher dielectric nanofluid viscosity and higher density of dielectric-nanofluids have resulted in larger pressure drop which limits energy efficiency in cooling systems.
- Variation in thermal and dielectric performance: Experimental results are inconsistent in many studies due to varied nanoparticle type, concentration, and preparation. The effect of turbulent flow on heat transfer should be explored more. Unified theory on breakdown strength improvement mechanisms is missing (particularly for different types of nanoparticles)
- High production costs: Expensive and complex techniques required for the synthesis of nanoparticles and the preparation of nanofluids. Industrial-scale mass production is time-consuming and expensive.
- Potential incompatibility and aging issues: Nanoparticles can have a detrimental interaction with solid insulation materials of the transformers, which can result in the long-term degradation. Also, conventional filtration/regeneration systems cannot be used for nanofluids thus raising the maintenance cost.
- Environmental and toxicity issues: Some nanoparticles can be corrosive or toxic, green alternatives are necessary. The disposal and lifecycle analysis of dielectric nanofluids has yet to be explored.

B. FUTURE RESEARCH DIRECTIONS

- Multidisciplinary: Converge knowledge from chemistry, materials science, thermal engineering, and physics to address issues in dielectric nanofluids holistically.
- Assessment of ecological consequences: Analysis of dielectric nanofluids on environmental effects.
- Enhanced stabilization and dispersion: The development of more effective surfactants and surface modification techniques to minimize agglomeration and sedimentation. Develop long-term stable eco-friendly biodegradable surfactant
- Nanoparticle property optimization: Study hybrid and doped nanoparticles for the balance between increase in thermo-dielectric properties and reduction in viscosity.
- Industrial testing and high-volume manufacturing: Conduct real-world (e.g., in pilot transformers) testing under real-world operating conditions to assess real-time performance over time. Create a scalable and low-cost process for producing dielectric nanofluids.
- Experimental studies at advanced levels: Study on dielectric nanofluids in turbulent flow regime and solid-liquid (i.e., nanoparticle and base fluid) interactions.
- Integrating systems: Investigate forced and natural cooling system with dielectric nanofluids. Explore the impact of volume fraction of nanoparticles on pump power and system efficiency.

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REFERENCES

[1] M. Karatas and Y. Bicen, "Nanoparticles for next-generation transformer insulating fluids: A review," *Renew. Sustain. Energy Rev.*, vol. 167, Oct. 2022, Art. no. 112645.

[2] M. Rafiq, M. Shafique, A. Azam, and M. Ateeq, "Transformer oil-based nanofluid: The application of nanomaterials on thermal, electrical and physicochemical properties of liquid insulation—A review," *Ain Shams Eng. J.*, vol. 12, no. 1, pp. 555–576, Mar. 2021.

[3] D. Peterchuck and A. Pahwa, "Sensitivity of transformer's hottest-spot and equivalent aging to selected parameters," *IEEE Trans. Power Del.*, vol. 17, no. 4, pp. 996–1001, Oct. 2002.

[4] F. Atalar, A. Ersoy, and P. Rozga, "Experimental investigation of the effect of nano particles on the breakdown strength of transformer liquids by harmonic current analysis," *Electr. Power Syst. Res.*, vol. 221, Aug. 2023, Art. no. 109390.

[5] F. Atalar, A. Ersoy, and P. Rozga, "Investigation of effects of different high voltage types on dielectric strength of insulating liquids," *Energies*, vol. 15, no. 21, p. 8116, Oct. 2022.

[6] Z. Shen, F. Wang, Z. Wang, and J. Li, "A critical review of plant-based insulating fluids for transformer: 30-year development," *Renew. Sustain. Energy Rev.*, vol. 141, May 2021, Art. no. 110783.

[7] K. N. Koutras, G. D. Peppas, T. T. Fetsis, S. N. Tegopoulos, V. P. Charalampakos, A. Kyritsis, A. G. Yiotis, I. F. Gonos, and E. C. Pyrgioti, "Dielectric and thermal response of TiO_2 and SiC natural ester based nanofluids for use in power transformers," *IEEE Access*, vol. 10, pp. 79222–79236, 2022.

[8] A. J. Christina, M. A. Salam, Q. M. Rahman, F. Wen, S. P. Ang, and W. Voon, "Causes of transformer failures and diagnostic methods—A review," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 1442–1456, Feb. 2018.

[9] M. N. Lyutikova, S. M. Korobeynikov, U. M. Rao, and I. Fofana, "Mixed insulating liquids with mineral oil for high-voltage transformer applications: A review," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 29, no. 2, pp. 454–461, Apr. 2022.

[10] N. Hemalatha, A. S. Kamaraja, A. Bhuvanesh, and K. Karthik Kumar, "Analysis on insulating characteristics of natural high oleic ester and mineral oil based blended oil under accelerated thermal aging exposure," *Biomass Convers. Biorefinery*, vol. 14, no. 23, pp. 30383–30400, Dec. 2024.

[11] L. M. Dumitran, A. Ciuriuc, and P. V. Notingher, "Thermal ageing effects on the dielectric properties and moisture content of vegetable and mineral oil used in power transformers," in *Proc. 8TH Int. Symp. Adv. TOPICS Electr. Eng. (ATEE)*, May 2013, pp. 1–6.

[12] S.-Q. Wang, G.-J. Zhang, J.-L. Wei, S.-S. Yang, M. Dong, and X.-B. Huang, "Investigation on dielectric response characteristics of thermally aged insulating pressboard in vacuum and oil-impregnated ambient," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 6, pp. 1853–1862, Dec. 2010.

[13] W. Zhang, "Partial discharge features of insulation for PowerElectronic transformers under time-temperature ageing," *CPSS Trans. Power Electron. Appl.*, vol. 8, no. 4, pp. 363–371, Dec. 2023.

[14] R. Chen, Q. Qiu, X. Peng, and C. Tang, "Surface modified h-BN towards enhanced electrical properties and thermal conductivity of natural ester insulating oil," *Renew. Energy*, vol. 204, pp. 185–196, Mar. 2023.

[15] S. U. S. Choi, "Enhancing thermal conductivity of fluids with nanoparticles," *Am. Soc. Mech. Eng. Fluids Eng. Div. FED*, vol. 231, pp. 99–105, Jan. 1995.

[16] U. S. Behera, J. S. Sangwai, and H.-S. Byun, "A comprehensive review on the recent advances in applications of nanofluids for effective utilization of renewable energy," *Renew. Sustain. Energy Rev.*, vol. 207, Jan. 2025, Art. no. 114901.

[17] A. K. Hussein, F. L. Rashid, M. K. Rasul, A. Basem, O. Younis, R. Z. Homod, M. E. H. Attia, M. A. Al-Obaidi, M. B. Ben Hamida, B. Ali, and S. F. Abdulameer, "A review of the application of hybrid nanofluids in solar still energy systems and guidelines for future prospects," *Sol. Energy*, vol. 272, Apr. 2024, Art. no. 112485.

[18] K. Ramesh, S. Vemulawada, S. U. Khan, S. Saleem, A. Sharma, R. K. Lodhi, and V. Kuppalapalle, "Peristaltic propulsion of Jeffrey nanofluid with heat and electromagnetic effects: Application to biomedicine," *Multiscale Multidisciplinary Model., Experiments Design*, vol. 7, no. 6, pp. 6151–6170, Nov. 2024.

[19] H. B. Bacha, N. Ullah, A. Hamid, and N. A. Shah, "A comprehensive review on nanofluids: Synthesis, cutting-edge applications, and future prospects," *Int. J. Thermofluids*, vol. 22, May 2024, Art. no. 100595.

[20] Z. Ullah, E. R. El-Zahar, L. F. Seddek, N. Becheikh, B. M. Alshammari, M. S. Aldhabani, and L. Kolsi, "Solar radiation and heat sink impact on fluctuating mixed convective flow and heat rate of Darcian nanofluid: Applications in electronic cooling systems," *Case Stud. Thermal Eng.*, vol. 59, Jul. 2024, Art. no. 104592.

[21] N. H. Hamad, A. M. Adham, and R. S. Abdullah, "Cooling electronic components by using nanofluids: A review," *J. Thermal Anal. Calorimetry*, vol. 149, no. 22, pp. 12503–12514, Nov. 2024.

[22] H. Khelifa, E. Vagnon, and A. Beroual, "AC breakdown voltage and partial discharge activity in synthetic ester-based fullerene and graphene nanofluids," *IEEE Access*, vol. 10, pp. 5620–5634, 2022.

[23] N. S. Suhaimi, M. T. Ishak, A. R. A. Rahman, M. F. M. Din, M. Z. Z. Abidin, and A. K. Khairi, "A review on palm oil-based nanofluids as a future resource for green transformer insulation system," *IEEE Access*, vol. 10, pp. 103563–103586, 2022.

[24] M. Furqan Hameed, G. A. Hussain, Y. Qayyum Gill, F. Mahmood, and A. Yousaf, "Enhancement of physical and electrical properties of mustard oil by adding TiO_2 nanotubes for power transformers," *IEEE Access*, vol. 12, pp. 95461–95471, 2024.

[25] D. Perez-Rosa, B. Garcia, and J. C. Burgos, "Dielectric response of the oil-paper insulation system in nanofluid-based transformers," *IEEE Access*, vol. 9, pp. 83797–83805, 2021.

[26] M. Badawi, S. A. Ibrahim, D.-E.-A. Mansour, S. A. Ward, A. A. El-Faraskoury, M. Ghali, K. Mahmoud, M. Lehtonen, and M. M. F. Darwish, "On highlighting the merits of gas-to-liquid transformer oil under accelerated thermal aging and faults: Electrical and physio- chemical properties," *IEEE Access*, vol. 12, pp. 93372–93388, 2024.

[27] R. A. Elsad, S. A. Mansour, and M. A. Izzularab, "Loading different sizes of titania nanoparticles into transformer oil: A study on the dielectric behavior," *J. Sol-Gel Sci. Technol.*, vol. 93, no. 3, pp. 615–622, Mar. 2020.

[28] 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.

[29] K. N. Koutras, A. E. Antonelou, I. A. Naxakis, V. P. Charalampakos, E. C. Pyrgioti, and S. N. Yannopoulos, "In-situ high temperature study of the long-term stability and dielectric properties of nanofluids based on TiO_2 and SiC dispersions in natural ester oil at various concentrations," *J. Mol. Liquids*, vol. 359, Aug. 2022, Art. no. 119284.

[30] S. K. Amizhtan, A. J. Amalanathan, R. Sarathi, B. Srinivasan, R. L. Gardas, H. Edin, and N. Taylor, "Impact of surfactants on the electrical and rheological aspects of silica based synthetic ester nanofluids," *IEEE Access*, vol. 10, pp. 18192–18200, 2022.

[31] R. A. Farade, N. I. Abdul Wahab, D.-E.-A. Mansour, N. Junaidi, M. E. M. Soudagar, R. K. Rajamony, and A. AlZubaidi, "A review on ultrasonic alchemy of oil-based nanofluids for cutting-edge dielectric and heat transfer oils," *J. Mol. Liquids*, vol. 408, Aug. 2024, Art. no. 125312.

[32] M. M. Bhunia, K. K. Chattopadhyay, and P. Chattopadhyay, "Ultrastable transformer oil nanofluids with significant AC breakdown voltage enhancement at ultra-low filler fraction of functionalized boron nitride nanosheets," ChemRxiv, Tech. Rep., 2022, pp. 1–23.

[33] W. Yu and H. Xie, "A review on nanofluids: Preparation, stability mechanisms, and applications," *J. Nanomaterials*, vol. 2012, no. 1, pp. 1–11, Jan. 2012.

[34] M. I. Qureshi and B. Qureshi, "Probing the use of silane-grafted fumed silica nanoparticles to produce stable transformer oil-based nanofluids," *Materials*, vol. 14, no. 24, p. 7649, Dec. 2021.

[35] M. Parvar, S. Saedodin, and S. H. Rostamian, "Journal of heat and mass transfer research experimental study on the thermal conductivity and viscosity of a transformer oil- based nanofluid containing ZnO nanoparticles," *J. Heat Mass Transf. Res.*, vol. 7, pp. 77–84, Apr. 2020.

[36] S. Porgar, H. F. Oztop, and S. Salehfekr, "A comprehensive review on thermal conductivity and viscosity of nanofluids and their application in heat exchangers," *J. Mol. Liquids*, vol. 386, Sep. 2023, Art. no. 122213.

[37] M. Fasehullah, F. Wang, and S. Jamil, "Significantly elevated AC dielectric strength of synthetic ester oil-based nanofluids by varying morphology of CdS nano-additives," *J. Mol. Liquids*, vol. 353, May 2022, Art. no. 118817.

[38] M. Rafiq, M. Shafique, A. Azam, and M. Ateeq, "The impacts of nanotechnology on the improvement of liquid insulation of transformers: Emerging trends and challenges," *J. Mol. Liquids*, vol. 302, Mar. 2020, Art. no. 112482.

[39] M. Srivastava, S. K. Goyal, and A. Saraswat, "Ester oil as an alternative to mineral transformer insulating liquid," *Mater. Today, Proc.*, vol. 43, pp. 2850–2854, Feb. 2021.

[40] 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.

[41] T. N. Kołtunowicz, "Dielectric insulation in medium- and high-voltage power equipment—Degradation and failure mechanism, diagnostics, and electrical parameters improvement," *Energies*, vol. 17, no. 11, p. 2704, Jun. 2024.

[42] R. Samikannu, R. Antony Raj, S. Murugesan, S. K. Venkatachary, and A. A. Stonier, "Assessing the dielectric performance of sclerocarya birrea (Marula oil) and mineral oil for eco-friendly power transformer applications," *Alexandria Eng. J.*, vol. 61, no. 1, pp. 355–366, Jan. 2022.

[43] R. A. Farade, N. I. A. Wahab, D.-E.-A. Mansour, and M. E. M. Soudagar, "The effect of nanoadditives in natural ester dielectric liquids: A comprehensive review on stability and thermal properties," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 30, no. 4, pp. 1478–1492, Aug. 2023.

[44] R. A. Farade, N. I. A. Wahab, D.-E.-A. Mansour, N. B. Azis, J. B. Jasni, M. E. M. Soudagar, and V. Siddappa, "Development of graphene oxide-based nonedible cottonseed nanofluids for power transformers," *Materials*, vol. 13, no. 11, p. 2569, Jun. 2020.

[45] G. D. P. Mahidhar, A. Somasundaram Karthikeyan, R. Sarathi, N. Taylor, and H. Edin, "Dielectric properties of mixed mineral and synthetic ester oil," *IET Sci., Meas. Technol.*, vol. 14, no. 9, pp. 704–714, Nov. 2020.

[46] A. Siddique, M. Yaqoob, W. Aslam, F. Zaffar, S. Atiq, and M. Usama Shahid, "A systematic review on promising development of cost-effective, biodegradable, and environment friendly vegetable based nanofluids as a future resource for green transformer insulation oil," *J. Mol. Liquids*, vol. 403, Jun. 2024, Art. no. 124836.

[47] B. Chakraborty, S. Maur, A. K. Pradhan, B. Chatterjee, and S. Dalai, "Study of nonlinearity, activation energy, and temperature effect on Al_2O_3 and TiO_2 nanoparticle-based mixed oil characteristics by dielectric spectroscopy," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 30, no. 3, pp. 997–1004, Jun. 2023.

[48] D. Amin, R. Walvekar, M. Khalid, M. Vaka, N. M. Mubarak, and T. C. S. M. Gupta, "Recent progress and challenges in transformer oil nanofluid development: A review on thermal and electrical properties," *IEEE Access*, vol. 7, pp. 151422–151438, 2019.

[49] I. Fofana, "50 years in the development of insulating liquids," *IEEE Elect. Insul. Mag.*, vol. 29, no. 5, pp. 13–25, Sep. 2013.

[50] M. Mazzaro, D. De Bartolomeo, E. Bemporad, S. Berardi, A. Ledda, L. Calcara, M. Pompili, M. Falconi, A. Vecchio, F. Scatiggio, A. Valant, M. Rebolini, A. Sturchio, and M. Salvadori, "Power transformer fire and environmental risk reduction by using natural esters," in *Proc. IEEE 19th Int. Conf. Dielectric Liquids (ICDL)*, Jun. 2017, pp. 1–4.

[51] M. Mazzaro, D. De Bartolomeo, M. Pompili, L. Calcara, S. Sangiovanni, F. Scatiggio, A. Valant, M. Rebolini, A. Ledda, E. Bemporad, S. Berardi, F. Mauri, M. Salvadori, A. Sturchio, and M. Falconi, "Fire simulation tests of mineral oil and natural esters transformers," in *Proc. IEEE 20th Int. Conf. Dielectric Liquids (ICDL)*, Jun. 2019, pp. 1–4.

[52] I. Razzaq, W. Xinhua, G. Rasool, T. Sun, A. S. Shflot, M. Y. Malik, K. Abbas, S. Ali, and A. Ali, "Nanofluids for advanced applications: A comprehensive review on preparation methods, properties, and environmental impact," *ACS Omega*, vol. 10, no. 6, pp. 5251–5282, Feb. 2025.

[53] N. S. Suhaimi, M. F. M. Din, M. T. Ishak, A. R. A. Rahman, J. Wang, and M. Z. Hassan, "Performance and limitation of mineral oil-based carbon nanotubes nanofluid in transformer application," *Alexandria Eng. J.*, vol. 61, no. 12, pp. 9623–9635, Dec. 2022.

[54] S. M. S. Murshed and P. Estellé, "A state of the art review on viscosity of nanofluids," *Renew. Sustain. Energy Rev.*, vol. 76, pp. 1134–1152, Sep. 2017.

[55] G. Dombek, Z. Nadolny, and A. Marcinkowska, "Effects of nanoparticles materials on heat transfer in electro-insulating liquids," *Appl. Sci.*, vol. 8, no. 12, p. 2538, Dec. 2018.

[56] M. Khalil, B. M. Jan, C. W. Tong, and M. A. Berawi, "Advanced nanomaterials in oil and gas industry: Design, application and challenges," *Appl. Energy*, vol. 191, pp. 287–310, Apr. 2017.

[57] R. A. Farade, N. I. A. Wahab, and D.-E.-A. Mansour, "The effect of nanoadditives in natural ester dielectric liquids: A comprehensive review on dielectric properties," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 30, no. 4, pp. 1502–1516, Aug. 2023.

[58] R. A. Farade, N. I. A. Wahab, D. A. Mansour, N. B. Azis, J. B. Jasni, V. Veerasamy, A. Vinayagam, B. M. Kotiyal, and T. M. Y. Khan, "The effect of interfacial zone due to nanoparticle–surfactant interaction on dielectric properties of vegetable oil based nanofluids," *IEEE Access*, vol. 9, pp. 107033–107045, 2021.

[59] E. J. Kadim, Z. A. Noorden, Z. Adzis, N. Azis, and N. A. Mohamad, "Surfactants effects on enhancing electrical performance of nanoparticle-based mineral transformer oil," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 30, no. 4, pp. 1573–1581, Aug. 2023.

[60] H. Babar, M. Sajid, and H. Ali, "Viscosity of hybrid nanofluids: A critical review," *Thermal Sci.*, vol. 23, no. 3, pp. 1713–1754, 2019.

[61] R. Rastogi, R. Kaushal, S. K. Tripathi, A. L. Sharma, I. Kaur, and L. M. Bharadwaj, "Comparative study of carbon nanotube dispersion using surfactants," *J. Colloid Interface Sci.*, vol. 328, no. 2, pp. 421–428, Dec. 2008.

[62] S. Mo, X. Shao, Y. Chen, and Z. Cheng, "Increasing entropy for colloidal stabilization," *Sci. Rep.*, vol. 6, no. 1, p. 36836, Nov. 2016.

[63] M. Navlani-García, D. Salinas-Torres, K. Mori, Y. Kuwahara, and H. Yamashita, "Tailoring the size and shape of colloidal noble metal nanocrystals as a valuable tool in catalysis," *Catalysis Surv. Asia*, vol. 23, no. 3, pp. 127–148, Sep. 2019.

[64] M. Rafiq, Y. Lv, C. Li, and Q. Sun, "Effect of Al_2O_3 nanorods on the performance of oil-impregnated pressboard insulation," *Electr. Eng.*, vol. 102, no. 2, pp. 715–724, Jun. 2020.

[65] S. S. Pillai, A. R. Aarathy, D. Gopinath, B. Aryanandiny, and B. Sankar, "Effects of magnetite and titania nanoparticles on properties of transformer insulating oil," *Nano Exp.*, vol. 1, no. 2, Sep. 2020, Art. no. 020040.

[66] L. Pislaru-Danescu, A. M. Morega, G. Telipan, M. Morega, J. B. Dumitru, and V. Marinescu, "Magnetic nanofluid applications in electrical engineering," *IEEE Trans. Magn.*, vol. 49, no. 11, pp. 5489–5497, Nov. 2013.

[67] S. A. Khan, M. Tariq, A. A. Khan, B. Alamri, and L. Mihet-Popa, "Influence of area and volume effect on dielectric behaviour of the mineral oil-based nanofluids," *Energies*, vol. 15, no. 9, p. 3354, May 2022.

[68] A. K. Das, "Investigation of electrical breakdown and heat transfer properties of coconut oil-based nanofluids," *Ind. Crops Products*, vol. 197, Jul. 2023, Art. no. 116545.

[69] M. F. Baharuddin, I. H. Zakaria, M. H. Ahmad, Z. Nawawi, M. A. B. Sidik, and M. I. Jambak, "Effect of surfactant on breakdown strength performance of transformer oil-based nanofluids," *J. Electr. Eng. Technol.*, vol. 14, no. 1, pp. 395–405, Jan. 2019.

[70] V. V. Wanatasanappan, M. Rezman, and M. Z. Abdullah, "Thermophysical properties of vegetable oil-based hybrid nanofluids containing Al_2O_3-TiO_2 nanoparticles as insulation oil for power transformers," *Nanomaterials*, vol. 12, no. 20, p. 3621, Oct. 2022.

[71] N. A. Mohamad, N. Azis, J. Jasni, M. Z. A. Ab Kadir, R. Yunus, and Z. Yaakub, "Impact of Fe_3O_4, CuO and Al_2O_3 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.

[72] H. Vaishnav, K. Navin, R. Kurchania, and R. J. Ball, "Synthesis of ZrO_2 based nanofluids for cooling and insulation of transformers," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 29, no. 1, pp. 199–205, Feb. 2022.

[73] S. K. Amizhtan, A. J. Amalanathan, M. S. Babu, R. Sarathi, G. Kumar, J. S. Sangwai, H. Edin, and N. Taylor, "Experimental study and ANN analysis of rheological behavior of mineral oil-based SiO_2 nanofluids," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 29, no. 3, pp. 956–964, Jun. 2022.

[74] E. Pyrgioti, N. Koutras, V. P. Charalampakos, G. D. Peppas, A. Bakandritsos, and I. Naxakis, "An experimental study on the influence of surface modification of TiO_2 nanoparticles on breakdown voltage of natural ester nanofluid," in *Proc. Int. Symp. High Voltage Eng.*, 2019, pp. 279–288.

[75] U. Khaled and A. Beroual, "Statistical investigation of AC dielectric strength of natural ester oil-based Fe_3O_4, Al_2O_3, and SiO_2 nano-fluids," *IEEE Access*, vol. 7, pp. 60594–60601, 2019.

[76] X. Zhao, M. Soltani, and K. Golovin, "Residue-Free droplet transport against gravity via wettability-patterned liquid-like surfaces," *Adv. Funct. Mater.*, vol. 34, no. 39, pp. 1–10, Jun. 2024.

[77] F. Ahangaran and A. H. Navarchian, "Recent advances in chemical surface modification of metal oxide nanoparticles with silane coupling agents: A review," *Adv. Colloid Interface Sci.*, vol. 286, Dec. 2020, Art. no. 102298.

[78] S. Shrestha, B. Wang, and P. Dutta, "Nanoparticle processing: Understanding and controlling aggregation," *Adv. Colloid Interface Sci.*, vol. 279, May 2020, Art. no. 102162.

[79] R. Walvekar, D. A. Zairin, M. Khalid, P. Jagadish, N. M. Mubarak, and T. C. S. M. Gupta, "Stability, thermo-physical and electrical properties of naphthenic/POME blended transformer oil nanofluids," *Thermal Sci. Eng. Prog.*, vol. 23, Jun. 2021, Art. no. 100878.

[80] R. A. Farade, N. I. Abdul Wahab, V. U. Siddiqui, and S. M. Sapuan, "Bio-based liquid nanocomposites for electrical equipment," *Phys. Sci. Rev.*, vol. 8943, pp. 1–24, Jul. 2025.

[81] M. M. Bhunia, K. K. Chattopadhyay, and P. Chattopadhyay, "Transformer oil nanofluids by two-dimensional hexagonal boron nitride nanofillers," *Electr. Eng.*, vol. 105, no. 2, pp. 813–825, Apr. 2023.

[82] Y. Chen, P. Luo, Q. Tao, X. Liu, and D. He, "Natural convective heat transfer investigation of nanofluids affected by electrical field with periodically changed direction," *Int. Commun. Heat Mass Transf.*, vol. 128, Nov. 2021, Art. no. 105613.

[83] K. N. Koutras, S. N. Tegopoulos, V. P. Charalampakos, A. Kyritsis, I. F. Gonos, and E. C. Pyrgioti, "Breakdown performance and partial discharge development in transformer oil-based metal carbide nanofluids," *Nanomaterials*, vol. 12, no. 2, p. 269, Jan. 2022.

[84] R. Singh, N. K. Sah, and V. Sharma, "Development and characterization of unitary and hybrid Al_2O_3 and ZrO dispersed jatropha oil-based nanofluid for cleaner production," *J. Cleaner Prod.*, vol. 317, Oct. 2021, Art. no. 128365.

[85] M. M. Bhunia, K. Panigrahi, C. B. Naskar, S. Bhattacharjee, K. K. Chattopadhyay, and P. Chattopadhyay, "2D square nanosheets of anatase TiO_2: A surfactant free nanofiller for transformer oil nanofluids," *J. Mol. Liquids*, vol. 325, Mar. 2021, Art. no. 115000.

[86] B. Chakraborty, K. Y. Raj, A. K. Pradhan, B. Chatterjee, S. Chakravorti, and S. Dalai, "Investigation of dielectric properties of TiO_2 and Al_2O_3 nanofluids by frequency domain spectroscopy at different temperatures," *J. Mol. Liquids*, vol. 330, May 2021, Art. no. 115642.

[87] 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.

[88] N. S. Suhaimi, M. F. M. Din, M. T. Ishak, A. R. A. Rahman, M. M. Ariffin, N. Hashim, and J. Wang, "Systematical study of multiwalled carbon nanotube nanofluids based disposed transformer oil," *Sci. Rep.*, vol. 10, no. 1, p. 20984, Dec. 2020.

[89] K. N. Koutras, I. A. Naxakis, A. E. Antonelou, V. P. Charalampakos, E. C. Pyrgioti, and S. N. Yannopoulos, "Dielectric strength and stability of natural ester oil based TiO_2 nanofluids," *J. Mol. Liquids*, vol. 316, Oct. 2020, Art. no. 113901.

[90] E. G. Atiya, D.-E.-A. Mansour, and M. A. Izzularab, "Partial discharge development in oil-based nanofluids: Inception, propagation and time transition," *IEEE Access*, vol. 8, pp. 181028–181035, 2020.

[91] J. Akhter, S. I. Gilani, H. H. Al-Kayiem, M. Ali, and F. Masood, "Experimental evaluation of thermophysical properties of oil-based titania nanofluids for medium temperature solar collectors," *Materialwissenschaft und Werkstofftechnik*, vol. 51, no. 6, pp. 792–802, Jun. 2020.

[92] W. U. Rehman, Z. M. A. Merican, A. H. Bhat, B. G. Hoe, A. A. Sulaimon, O. Akbarzadeh, M. S. Khan, A. Mukhtar, S. Saqib, A. Hameed, N. Mellon, H. Ullah, S. Ullah, and M. A. Assiri, "Synthesis, characterization, stability and thermal conductivity of multi-walled carbon nanotubes (MWCNTs) and eco-friendly jatropha seed oil based nanofluid: An experimental investigation and modeling approach," *J. Mol. Liquids*, vol. 293, Nov. 2019, Art. no. 111534.

[93] A. Hameed, A. Mukhtar, U. Shafiq, M. Qizilbash, M. S. Khan, T. Rashid, C. B. Bavoh, W. U. Rehman, and A. Guardo, "Experimental investigation on synthesis, characterization, stability, thermo-physical properties and rheological behavior of MWCNTs-kapok seed oil based nanofluid," *J. Mol. Liquids*, vol. 277, pp. 812–824, Mar. 2019.

[94] P. G. Kumar, R. Prabakaran, D. Sakthivadivel, P. Somasundaram, V. S. Vigneswaran, and S. C. Kim, "Ultrasonication time optimization for multi-walled carbon nanotube based therminol-55 nanofluid: An experimental investigation," *J. Thermal Anal. Calorimetry*, vol. 147, no. 19, pp. 10329–10336, Oct. 2022.

[95] S. S. Sonawane, R. S. Khedkar, and K. L. Wasewar, "Effect of sonication time on enhancement of effective thermal conductivity of nano TiO_2–water, ethylene glycol, and paraffin oil nanofluids and models comparisons," *J. Exp. Nanoscience*, vol. 10, no. 4, pp. 310–322, Mar. 2015.

[96] Z. Chen, A. Shahsavar, A. A. A. A. Al-Rashed, and M. Afrand, "The impact of sonication and stirring durations on the thermal conductivity of alumina-liquid paraffin nanofluid: An experimental assessment," *Powder Technol.*, vol. 360, pp. 1134–1142, Jan. 2020.

[97] A. K. Tiwari, N. S. Pandya, Z. Said, S. H. Chhatbar, Y. A. Al-Turki, and A. R. Patel, "3S (sonication, surfactant, stability) impact on the viscosity of hybrid nanofluid with different base fluids: An experimental study," *J. Mol. Liquids*, vol. 329, May 2021, Art. no. 115455.

[98] M. Fasehullah, F. Wang, S. Jamil, and M. S. Bhutta, "Influence of emerging semiconductive nanoparticles on AC dielectric strength of synthetic ester midel-7131 insulating oil," *Materials*, vol. 15, no. 13, p. 4689, Jul. 2022.

[99] Q. Luo, C. Wang, H. Wen, and L. Liu, "Research and optimization of thermophysical properties of sic oil-based nanofluids for data center immersion cooling," *Int. Commun. Heat Mass Transf.*, vol. 131, Feb. 2022, Art. no. 105863.

[100] J. Jacob, P. Preetha, and T. K. Sindhu, "Stability analysis and characterization of natural ester nanofluids for transformers," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 27, no. 5, pp. 1715–1723, Oct. 2020.

[101] J. Jacob, P. Preetha, and S. Thiruthi Krishnan, "Review on natural ester and nanofluids as an environmental friendly alternative to transformer mineral oil," *IET Nanodielectr.*, vol. 3, no. 2, pp. 33–43, Jun. 2020.

[102] S. O. Oparanti, A. A. Khaleed, and A. A. Abdelmalik, "Nanofluid from palm kernel oil for high voltage insulation," *Mater. Chem. Phys.*, vol. 259, Feb. 2021, Art. no. 123961.

[103] R. A. Farade, N. I. A. Wahab, D. A. Mansour, N. B. Azis, J. B. Jasni, V. Veerasamy, M. Thirumeni, A. X. R. Irudayaraj, and A. S. Murthy, "Investigation of the effect of sonication time on dispersion stability, dielectric properties, and heat transfer of graphene based green nanofluids," *IEEE Access*, vol. 9, pp. 50607–50623, 2021.

[104] E. G. Atiya, D. A. Mansour, R. M. Khattab, and A. M. Azmy, "Dispersion behavior and breakdown strength of transformer oil filled with TiO_2 nanoparticles," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2463–2472, Oct. 2015.

[105] G. Huminic and A. Huminic, "Application of nanofluids in heat exchangers: A review," *Renew. Sustain. Energy Rev.*, vol. 16, no. 8, pp. 5625–5638, Oct. 2012.

[106] M. A. Abid, I. Khan, Z. Ullah, K. Ullah, A. Haider, and S. M. Ali, "Dielectric and thermal performance up-gradation of transformer oil using valuable nano-particles," *IEEE Access*, vol. 7, pp. 153509–153518, 2019.

[107] M. Maharana, N. Baruah, S. K. Nayak, and N. Sahoo, "Nanofluid and transformer oil impregnated aged Kraft paper: Analysis of its mechanical strength," in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Oct. 2018, pp. 302–305.

[108] D. Dey, P. Kumar, and S. Samantaray, "A review of nanofluid preparation, stability, and thermo-physical properties," *Heat Transf.-Asian Res.*, vol. 46, no. 8, pp. 1413–1442, Dec. 2017.

[109] F. Ahmad, A. A. Khan, Q. Khan, and M. R. Hussain, "State-of-art in nano-based dielectric oil: A review," *IEEE Access*, vol. 7, pp. 13396–13410, 2019.

[110] M. Asefi, H. Molavi, N. M. Shariaty, D. J. Babaee, N. Nemati, M. Yavari, and M. Akbari, "An investigation on stability, electrical and thermal characteristics of transformer insulting oil nanofluids," *Int. J. Eng.*, vol. 29, no. 10, pp. 1332–1340, Oct. 2016.

[111] M. Javed, A. H. Shaik, T. A. Khan, M. Imran, A. Aziz, A. R. Ansari, and M. R. Chandan, "Synthesis of stable waste palm oil based CuO nanofluid for heat transfer applications," *Heat Mass Transf.*, vol. 54, no. 12, pp. 3739–3745, Dec. 2018.

[112] U. Khaled and A. Beroual, "AC dielectric strength of synthetic ester-based Fe_3O_4, Al_2O_3 and SiO_2 nanofluids—Conformity with normal and Weibull distributions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 26, no. 2, pp. 625–633, Apr. 2019.

[113] J. Taha-Tijerina, H. Ribeiro, K. Aviña, J. M. Martínez, A. P. Godoy, J. M. D. O. Cremonezzi, M. A. Luciano, M. A. Gimenes Benega, R. J. E. Andrade, G. J. M. Fechine, G. Babu, and S. Castro, "Thermal conductivity performance of 2D H-BN/MoS_2/-hybrid nanostructures used on natural and synthetic esters," *Nanomaterials*, vol. 10, no. 6, p. 1160, Jun. 2020.

[114] K. Maaz, S. Karim, A. Mashiatullah, J. Liu, M. D. Hou, Y. M. Sun, J. L. Duan, H. J. Yao, D. Mo, and Y. F. Chen, "Structural analysis of nickel doped cobalt ferrite nanoparticles prepared by coprecipitation route," *Phys. B, Condens. Matter*, vol. 404, no. 21, pp. 3947–3951, Nov. 2009.

[115] G. D. Peppas, A. Bakandritsos, V. P. Charalampakos, E. C. Pyrgioti, J. Tucek, R. Zboril, and I. F. Gonos, "Ultrastable natural ester-based nanofluids for high voltage insulation applications," *ACS Appl. Mater. Interfaces*, vol. 8, no. 38, pp. 25202–25209, Sep. 2016.

[116] H. Yasmin, S. O. Giwa, S. Noor, and H. Ş. Aybar, "Influence of preparation characteristics on stability, properties, and performance of mono- and hybrid nanofluids: Current and future perspective," *Machines*, vol. 11, no. 1, p. 112, Jan. 2023.

[117] M. R. Hussain, Q. Khan, A. A. Khan, S. S. Refaat, and H. Abu-Rub, "Dielectric performance of magneto-nanofluids for advancing oil-immersed power transformer," *IEEE Access*, vol. 8, pp. 163316–163328, 2020.

[118] 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.

[119] J. Jacob, S. Dhanya, L. Tharamal, A. A. Nelson, and P. Preetha, "Partial discharge characteristics of nanofilled mineral oil," in *Proc. IEEE Region 10 Symp. (TENSYMP)*, Jun. 2019, pp. 316–320.

[120] D. A. Mansour and A. M. Elsaeed, "Heat transfer properties of transformer oil-based nanofluids filled with Al_2O_3 nanoparticles," in *Proc. IEEE Int. Conf. Power Energy (PECon)*, Dec. 2014, pp. 123–127.

[121] R. Gayathri, P. Deiva Sundari, S. Thakur, and R. Sarathi, "Investigation on the dielectric performance of titania nanoparticles and surfactant added mixture of mineral and natural ester oil," *Mater. Res. Exp.*, vol. 6, no. 12, Nov. 2019, Art. no. 125020.

[122] V. A. Primo, D. Pérez-Rosa, B. García, and J. C. Cabanelas, "Evaluation of the stability of dielectric nanofluids for use in transformers under real operating conditions," *Nanomaterials*, vol. 9, no. 2, p. 143, Jan. 2019.

[123] D.-E.-A. Mansour and E. G. Atiya, "Application of UV/Vis spectroscopy to assess the stability of oil-based nanofluids," in *Proc. IEEE Conf. Electr. Insul. Dielectric Phenomena (CEIDP)*, Oct. 2016, pp. 671–674.

[124] S. A. Khan, A. A. Khan, and M. Tariq, "Measurement of tan-delta and DC resistivity of synthetic ester based oil filled with Fe_2O_3, TiO_2 and Al_2O_3 nanoparticles," *Smart Sci.*, vol. 9, no. 3, pp. 216–225, Jul. 2021.

[125] M. Rafiq, L. Chengrong, and Y. Lv, "Effect of Al_2O_3 nanorods on dielectric strength of aged transformer oil/paper insulation system," *J. Mol. Liquids*, vol. 284, pp. 700–708, Jun. 2019.

[126] J. Kurimský, M. Rajňák, R. Cimbala, J. Rajnič, M. Timko, and P. Kopčanský, "Effect of magnetic nanoparticles on partial discharges in transformer oil," *J. Magn. Magn. Mater.*, vol. 496, Feb. 2020, Art. no. 165923.

[127] J. Kudelcik, P. Bury, P. Kopcansky, and M. Timko, "Dielectric breakdown in mineral oil ITO 100 based magnetic fluid," *Phys. Proc.*, vol. 9, pp. 78–81, 2010.

[128] P. Havran, R. Cimbala, J. Kurimský, M. Rajňák, B. Dolník, D. Medved, and J. Király, "Dielectric relaxation response of electrical insulating liquids under different natures of thermal stress," *J. Mater. Res. Technol.*, vol. 25, pp. 1599–1611, Jul. 2023.

[129] N. Yadav, R. K. Jarial, and U. M. Rao, "Characterization of mineral oil based Fe_3O_4 nanofluid for application in oil filled transformers," *Int. J. Electr. Eng. Informat.*, vol. 10, no. 2, pp. 338–349, Jun. 2018.

[130] Z. Zhang, J. Li, P. Zou, and S. Grzybowski, "Electrical properties of nano-modified insulating vegetable oil," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectic Phenomena*, Oct. 2010, pp. 1–4.

[131] M. Nazari, M. H. Rasoulifard, and H. Hosseini, "Dielectric breakdown strength of magnetic nanofluid based on insulation oil after impulse test," *J. Magn. Magn. Mater.*, vol. 399, pp. 1–4, Feb. 2016.

[132] P. Zou, J. Li, C.-X. Sun, Z.-T. Zhang, and R.-J. Liao, "Dielectric properties and electrodynamic process of natural ester-based insulating nanofluid," *Modern Phys. Lett. B*, vol. 25, no. 25, pp. 2021–2031, Oct. 2011.

[133] Y. Lv, Y. Ge, Z. Sun, Q. Sun, M. Huang, C. Li, B. Qi, J. Yuan, and Z. Xing, "Effect of nanoparticle morphology on pre-breakdown and breakdown properties of insulating oil-based nanofluids," *Nanomaterials*, vol. 8, no. 7, p. 476, Jun. 2018.

[134] N. V. Thanh, N. T. H. Ngoc, D. M. Thuy, L. V. Tuynh, H. H. Son, and N. P. Long, "Highly improved dielectric and thermal performance of polyalphaolefin oil-based fluids using MgO nanoparticles," *Coatings*, vol. 13, no. 5, p. 931, May 2023.

[135] Y.-Z. Lv, X.-X. Li, Y.-F. Du, F.-C. Wang, and C.-R. Li, "Preparation and breakdown strength of TiO_2 fluids based on transformer oil," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectic Phenomena*, Oct. 2010, pp. 1–3.

[136] R. A. Farade, N. I. B. A. Wahab, D. A. Mansour, N. B. Azis, J. Jasni, N. R. Banapurmath, and M. E. M. Soudagar, "Investigation of the dielectric and thermal properties of non-edible cottonseed oil by infusing h-BN nanoparticles," *IEEE Access*, vol. 8, pp. 76204–76217, 2020.

[137] N. Kutlu, R. Pandiselvam, A. Kamiloglu, I. Saka, N. U. Sruthi, A. Kothakota, C. T. Socol, and C. M. Maerescu, "Impact of ultrasonication applications on color profile of foods," *Ultrason. Sonochemistry*, vol. 89, Sep. 2022, Art. no. 106109.

[138] F. Yu, Y. Chen, X. Liang, J. Xu, C. Lee, Q. Liang, P. Tao, and T. Deng, "Dispersion stability of thermal nanofluids," *Prog. Natural Sci., Mater. Int.*, vol. 27, no. 5, pp. 531–542, Oct. 2017.

[139] S. Saleem, I. L. Animasaun, S.-J. Yook, Q. M. Al-Mdallal, N. A. Shah, and M. Faisal, "Insight into the motion of water conveying three kinds of nanoparticles shapes on a horizontal surface: Significance of thermo-migration and Brownian motion," *Surf. Interfaces*, vol. 30, Jun. 2022, Art. no. 101854.

[140] J. Wang, Y. Sun, M. Yu, X. Lu, S. Komarneni, and C. Yang, "Emulsions stabilized by highly hydrophilic TiO_2 nanoparticles via van der Waals attraction," *J. Colloid Interface Sci.*, vol. 589, pp. 378–387, May 2021.

[141] W. N. Bond, "LXXXII.Bubbles and drops and Stokes' law," *London, Edinburgh, Dublin Phil. Mag. J. Sci.*, vol. 4, no. 24, pp. 889–898, Nov. 1927.

[142] L. Fu, Z. Ren, L. Jiang, W. Chen, W. Ding, K. Liao, X. Qiu, L. Chen, and M. Shao, "Preparation of MoS_2/diesel dispersion nanofluid and its application in diluent blending-viscosity reduction technology for heavy oil production," *Asia–Pacific J. Chem. Eng.*, vol. 18, no. 5, p. 2961, Sep. 2023.

[143] M. Sandhya, D. Ramasamy, K. Sudhakar, K. Kadirgama, and W. S. W. Harun, "Ultrasonication an intensifying tool for preparation of stable nanofluids and study the time influence on distinct properties of graphene nanofluids—A systematic overview," *Ultrason. Sonochemistry*, vol. 73, May 2021, Art. no. 105479.

[144] H. Pourpasha, S. Zeinali Heris, and S. B. Mousavi, "Thermal performance of novel $ZnFe_2O_4$ and TiO_2-doped MWCNT nanocomposites in transformer oil," *J. Mol. Liquids*, vol. 394, Jan. 2024, Art. no. 123727.

[145] I. Fernández, R. Valiente, F. Ortiz, C. J. Renedo, and A. Ortiz, "Effect of TiO_2 and ZnO nanoparticles on the performance of dielectric nanofluids based on vegetable esters during their aging," *Nanomaterials*, vol. 10, no. 4, p. 692, Apr. 2020.

[146] S. A. Khan, M. Tariq, A. A. Khan, and B. Alamri, "Effect of iron/titania-based nanomaterials on the dielectric properties of mineral oil, natural and synthetic esters as transformers insulating fluid," *IEEE Access*, vol. 9, pp. 168971–168980, 2021.

[147] M. T. Chaichan, H. A. Kazem, M. K. S. Al-Ghezi, A. H. A. Al-Waeli, A. J. Ali, K. Sopian, A. A. H. Kadhum, W. N. R. Wan Isahak, M. S. Takriff, and A. A. Al-Amiery, "Optimizing MWCNT-based nanofluids for photovoltaic/thermal cooling through preparation parameters," *ACS Omega*, vol. 8, no. 33, pp. 29910–29925, Aug. 2023.

[148] M. T. Chaichan, H. A. Kazem, M. K. S. Al-Ghezi, A. H. A. Al-Waeli, A. J. Ali, K. Sopian, A. A. H. Kadhum, W. N. R. W. Isahak, M. S. Takriff, and A. A. Al-Amiery, "Effect of different preparation parameters on the stability and thermal conductivity of MWCNT-based nanofluid used for photovoltaic/thermal cooling," *Sustainability*, vol. 15, no. 9, p. 7642, May 2023.

[149] G. Shukla and H. Aiyer, "Thermal conductivity enhancement of transformer oil using functionalized nanodiamonds," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 4, pp. 2185–2190, Aug. 2015.

[150] Y.-Z. Lv, C. Li, Q. Sun, M. Huang, C.-R. Li, and B. Qi, "Effect of dispersion method on stability and dielectric strength of transformer oil-based TiO_2 nanofluids," *Nanosc. Res. Lett.*, vol. 11, no. 1, p. 515, Dec. 2016.

[151] L. Dan, K. Zhang, Q. Wang, and N. Liu, "Surface modification boosts dispersion stability of nanoparticles in dielectric fluids," *J. Ind. Eng. Chem.*, vol. 132, pp. 518–528, Apr. 2024.

[152] I. H. Zakaria, M. H. Ahmad, Z. Abdul-Malek, M. A. B. Sidik, Z. Nawawi, and M. I. Jambak, "AC breakdown strength performance of plasma treated mineral oil-based nanofluids," in *Proc. Int. Conf. Electr. Eng. Comput. Sci. (ICECOS)*, Aug. 2017, pp. 333–337.

[153] Y. Mohammadfam and S. Zeinali Heris, "An experimental study of the influence of Fe_3O_4, MWCNT-Fe_3O_4, and Fe_3O_4@MWCNT nanoparticles on the thermophysical characteristics and laminar convective heat transfer of nanofluids: A comparative study," *Surf. Interfaces*, vol. 43, Dec. 2023, Art. no. 103506.

[154] U. Mohan Rao, I. Fofana, T. Jaya, E. M. Rodriguez-Celis, J. Jalbert, and P. Picher, "Alternative dielectric fluids for transformer insulation system: Progress, challenges, and future prospects," *IEEE Access*, vol. 7, pp. 184552–184571, 2019.

[155] M. Rajňák, J. Kurimský, R. Cimbala, Z. Čonka, P. Bartko, M. Šuga, K. Paulovičová, J. Tóthová, M. Karpets, P. Kopčanský, and M. Timko, "Statistical analysis of AC dielectric breakdown in transformer oil-based magnetic nanofluids," *J. Mol. Liquids*, vol. 309, Jul. 2020, Art. no. 113243.

[156] C. P. Y. Alicia, W. Rashmi, M. Khalid, A. K. Rasheed, and T. Gupta, "Synthesis and thermo-physical characterization of graphene based transformer oil," *J. Eng. Sci. Technol.*, vol. 11, pp. 140–152, Oct. 2016.

[157] T. S. Sreeremya, A. Krishnan, A. Peer Mohamed, U. S. Hareesh, and S. Ghosh, "Synthesis and characterization of cerium oxide based nanofluids: An efficient coolant in heat transport applications," *Chem. Eng. J.*, vol. 255, pp. 282–289, Nov. 2014.

[158] H. Pourpasha, S. Zeinali Heris, and M. Mohammadpourfard, "The effect of TiO_2 doped multi-walled carbon nanotubes synthesis on the thermo-physical and heat transfer properties of transformer oil: A comprehensive experimental study," *Case Stud. Thermal Eng.*, vol. 41, Jan. 2023, Art. no. 102607.

[159] S. Hussain, M. Mottahir Alam, M. Imran, N. Zouli, A. Aziz, K. Irshad, M. Haider, and A. Khan, "Fe_3O_4 nanoparticles decorated multi-walled carbon nanotubes based magnetic nanofluid for heat transfer application," *Mater. Lett.*, vol. 274, Sep. 2020, Art. no. 128043.

[160] H. Alizadeh, H. Pourpasha, S. Zeinali Heris, and P. Estellé, "Experimental investigation on thermal performance of covalently functionalized hydroxylated and non-covalently functionalized multi-walled carbon nanotubes/transformer oil nanofluid," *Case Stud. Thermal Eng.*, vol. 31, Mar. 2022, Art. no. 101713.

[161] Z.-B. Qin, L. Tan, Z.-Q. Liu, S. Chen, J.-H. Qin, J.-J. Tang, and N. Li, "One-pot synthesis of ultrafine TiO_2 nanoparticles with enhanced thermal conductivity for nanofluid applications," *Adv. Powder Technol.*, vol. 27, no. 2, pp. 299–304, Mar. 2016.

[162] A. H. Mashhadzadeh, M. Ghanbari, A. Koochaki, S. Seyyedbarzegar, and M. G. Ahangari, "Partial discharge elimination in transformer oils by nanofluids: From theory to practice," *Arabian J. Sci. Eng.*, vol. 48, no. 5, pp. 6253–6270, May 2023.

[163] S. O. Oparanti, A. A. Abdelmalik, A. A. Khaleed, J. K. Abifarin, M. U. Suleiman, and V. E. Oteikwu, "Synthesis and characterization of cooling biodegradable nanofluids from non-edible oil for high voltage application," *Mater. Chem. Phys.*, vol. 277, Feb. 2022, Art. no. 125485.

[164] A. J. Amalanathan, M. Zdanowski, and R. Sarathi, "Streaming electrification of different insulating fluids in power transformers," *Energies*, vol. 15, no. 21, p. 8121, Oct. 2022.

[165] R. C. Rabelo Neto, D. O. Lima, T. D. S. Pinheiro, R. F. Almeida, T. N. Castro Dantas, M. S. G. Dantas, M. A. S. Araújo, C. L. Cavalcante, and D. C. S. Azevedo, "Thermo-oxidative stability of mineral naphthenic insulating oils: Combined effect of antioxidants and metal passivator," *Ind. Eng. Chem. Res.*, vol. 43, no. 23, pp. 7428–7434, Nov. 2004.

[166] L. S. Oumert, D. Rahal, A. H.-Z. Zafour, and I. Fofana, "Caracterization and rheological behaviour of a used insulating oil and a transformer sludge," in *Proc. Algerian Large Electr. Netw. Conf. (CAGRE)*, Feb. 2019, pp. 1–5.

[167] A. Balkrishna, A. Kumar, V. Arya, A. Rohela, R. Verma, E. Nepovimova, O. Krejcar, D. Kumar, N. Thakur, and K. Kuca, "Phytoantioxidant functionalized nanoparticles: A green approach to combat nanoparticle-induced oxidative stress," *Oxidative Med. Cellular Longevity*, vol. 2021, no. 1, pp. 1–17, Jan. 2021.

[168] A. Nazrin, T. M. Kuan, D.-E.-A. Mansour, R. A. Farade, A. M. Ariffin, M. S. A. Rahman, and N. I. B. Abdul Wahab, "Innovative approaches for augmenting dielectric properties in cross-linked polyethylene (XLPE): A review," *Heliyon*, vol. 10, no. 15, Aug. 2024, Art. no. e34737.

[169] R. A. Farade, D.-E.-A. Mansour, N. I. A. Wahab, M. K. A. Ariffin, R. F. Emara, M. M. Emara, M. K. El-Nemr, and R. K. Rajamony, "Deeper insight into thermal conductivity, size, sedimentation, band gap, and moisture effect of nanoparticles on thermo-dielectric performance of nanofluids," *J. Mol. Liquids*, vol. 434, Sep. 2025, Art. no. 127986.

[170] A. M. Samy, M. E. Ibrahim, A. M. Abd-Elhady, and M. A. Izzularab, "On electric field distortion for breakdown mechanism of nanofilled transformer oil," *Int. J. Electr. Power Energy Syst.*, vol. 117, May 2020, Art. no. 105632.

[171] P. Muangpratoom, A. Kunakorn, N. Pattanadech, and W. Vittayakorn, "Effect of different temperatures on AC breakdown voltage of mineral oil based nanofluids," in *Proc. 15th Int. Conf. Electr. Eng./Electron., Comput., Telecommun. Inf. Technol. (ECTI-CON)*, Jul. 2018, pp. 536–539.

[172] V. A. Primo, B. García, J. C. Burgos, and D. Pérez-Rosa, "Investigation of the lightning impulse breakdown voltage of mineral oil based Fe_3O_4 nanofluids," *Coatings*, vol. 9, no. 12, p. 799, Nov. 2019.

[173] Y. Lv, M. Rafiq, C. Li, and B. Shan, "Study of dielectric breakdown performance of transformer oil based magnetic nanofluids," *Energies*, vol. 10, no. 7, p. 1025, Jul. 2017.

[174] W. Sima, J. Shi, Q. Yang, S. Huang, and X. Cao, "Effects of conductivity and permittivity of nanoparticle on transformer oil insulation performance: Experiment and theory," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 1, pp. 380–390, Feb. 2015.

[175] 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. Appl. Phys.*, vol. 107, no. 1, Jan. 2010, Art. no. 014310.

[176] J. G. Hwang, M. Zahn, L. A. A. Pettersson, O. Hjortstam, and R. Liu, "Electron scavenging by conductive nanoparticles in oil insulated power transformers," in *Proc. Electrost. Jt. Conf.*, 2009, pp. 1–12.

[177] M. Z. H. Makmud, H. A. Illias, C. Y. Chee, and S. Z. A. Dabbak, "Partial discharge in nanofluid insulation material with conductive and semiconductive nanoparticles," *Materials*, vol. 12, no. 5, p. 816, Mar. 2019.

[178] B. Chakraborty, S. Maur, A. Kumar Pradhan, B. Chatterjee, and S. Dalai, "Investigations on dielectric characteristics of hybrid nanofluids through time and frequency domain spectroscopic measurement," *J. Mol. Liquids*, vol. 366, Nov. 2022, Art. no. 120347.

[179] J.-C. Lee and W.-Y. Kim, "Experimental study on the dielectric breakdown voltage of the insulating oil mixed with magnetic nanoparticles," *Phys. Proc.*, vol. 32, pp. 327–334, Jan. 2012.

[180] D.-E.-A. Mansour, I. B. M. Taha, R. A. Farade, and N. I. B. A. Wahab, "Partial discharge diagnosis in GIS based on pulse sequence features and optimized machine learning classification techniques," *Electric Power Syst. Res.*, vol. 211, Oct. 2022, Art. no. 108162.

[181] J. Q. Chan, W. J. K. Raymond, H. A. Illias, and M. Othman, "Partial discharge localization techniques: A review of recent progress," *Energies*, vol. 16, no. 6, p. 2863, Mar. 2023.

[182] D. Liu, Y. Zhou, Y. Yang, L. Zhang, and F. Jin, "Characterization of high performance AlN nanoparticle-based transformer oil nanofluids," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 2757–2767, Oct. 2016.

[183] J. Kurimský, M. Rajňák, M. Šárpataky, Z. Čonka, and K. Paulovičová, "Electrical and acoustic investigation of partial discharges in two types of nanofluids," *J. Mol. Liquids*, vol. 341, Nov. 2021, Art. no. 117444.

[184] Z. Sun, Y. Ge, Y. Lv, M. Huang, C. Li, and Y. Du, "The effects of TiO_2 nanoparticles on insulation and charge transport characteristics of aged transformer oil," in *Proc. IEEE 20th Int. Conf. Dielectric Liquids (ICDL)*, Jun. 2019, pp. 1–4.

[185] Y. Zhong, Y. Lv, C. Li, Y. Du, M. Chen, S. Zhang, Y. Zhou, and L. Chen, "Insulating properties and charge characteristics of natural ester fluid modified by TiO_2 semiconductive nanoparticles," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 1, pp. 135–140, Feb. 2013.

[186] H. C. Verma and A. Baral, "Dielectric frequency response at different voltage levels of mineral oil-based silica nanofluids," *Ain Shams Eng. J.*, vol. 14, no. 7, Jul. 2023, Art. no. 101994.

[187] M. M. Emara, D. A. Mansour, and A. M. Azmy, "Mitigating the impact of aging byproducts in transformer oil using TiO_2 nanofillers," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 6, pp. 3471–3480, Dec. 2017.

[188] M. M. Bhunia, K. Panigrahi, S. Das, K. K. Chattopadhyay, and P. Chattopadhyay, "Amorphous graphene—Transformer oil nanofluids with superior thermal and insulating properties," *Carbon*, vol. 139, pp. 1010–1019, Nov. 2018.

[189] Z. Taghikhani, M. A. Taghikhani, and G. B. Gharehpetian, "Comprehensive comparative analysis of metal-oxide nanoadditives impacts on oil-filled finemet and vitroperm alloy core transformers HST concerning nanofluid thermophysical properties accurate estimation," *Energy Convers. Manage.*, vol. 260, May 2022, Art. no. 115594.

[190] G. W. Swift, "Adaptive transformer thermal overload protection," *IEEE Trans. Power Deliv.*, vol. 16, no. 4, pp. 516–521, Aug. 2001.

[191] S. U. Ilyas, M. Narahari, J. T. Y. Theng, and R. Pendyala, "Experimental evaluation of dispersion behavior, rheology and thermal analysis of functionalized zinc oxide-paraffin oil nanofluids," *J. Mol. Liquids*, vol. 294, Nov. 2019, Art. no. 111613.

[192] A. Amiri, M. Shanbedi, G. Ahmadi, and S. Rozali, "Transformer oils-based graphene quantum dots nanofluid as a new generation of highly conductive and stable coolant," *Int. Commun. Heat Mass Transf.*, vol. 83, pp. 40–47, Apr. 2017.

[193] C. Choi, H. S. Yoo, and J. M. Oh, "Preparation and heat transfer properties of nanoparticle-in-transformer oil dispersions as advanced energy-efficient coolants," *Current Appl. Phys.*, vol. 8, no. 6, pp. 710–712, Oct. 2008.

[194] S. Aberoumand and A. Jafarimoghaddam, "Tungsten (III) oxide (WO3)—Silver/transformer oil hybrid nanofluid: Preparation, stability, thermal conductivity and dielectric strength," *Alexandria Eng. J.*, vol. 57, no. 1, pp. 169–174, Mar. 2018.

[195] M. Nazari, S. Jafarmadar, and S. Gohery, "Convective heat transfer behavior and AC dielectric breakdown voltage of electric power transformer oil with magnetic colloidal nano-fluid: An experimental study," *Case Stud. Thermal Eng.*, vol. 45, May 2023, Art. no. 103017.

[196] T. Ramamurthy and S. Krishnan, "Influence of viscosity on the thermal behavior of fluids in a sealed can," *Alexandria Eng. J.*, vol. 61, no. 10, pp. 7833–7842, Oct. 2022.

[197] A. K. Kalajahi and P. S. Ghahfarokhi, "High-viscosity spray cooling system for high-reliability motor drives in electric vehicles: A review," *IEEE Trans. Transport. Electrific.*, vol. 11, no. 1, pp. 3418–3432, Feb. 2025.

[198] T. K. Saha and P. Purkait, "Transformer ageing: Monitoring and estimation techniques," in *Transformer Insulation Materials and Ageing*. Hoboken, NJ, USA: Wiley, 2017, pp. 1–33.

[199] S. O. Oparanti, I. Fofana, R. Jafari, and R. Zarrougui, "A state-of-the-art review on green nanofluids for transformer insulation," *J. Mol. Liquids*, vol. 396, Feb. 2024, Art. no. 124023.

[200] I. Akande, T. Bridgwater, P. J. Van Koningsbruggen, and Q. Yuan, "A viscosity study of charcoal-based nanofluids towards enhanced oil recovery," *J. Mol. Liquids*, vol. 387, Oct. 2023, Art. no. 122615.

[201] V. Mentlik, P. Trnka, J. Hornak, and P. Totzauer, "Development of a biodegradable electro-insulating liquid and its subsequent modification by nanoparticles," *Energies*, vol. 11, no. 3, p. 508, Feb. 2018.

[202] M. A. Khairul, K. Shah, E. Doroodchi, R. Azizian, and B. Moghtaderi, "Effects of surfactant on stability and thermo-physical properties of metal oxide nanofluids," *Int. J. Heat Mass Transf.*, vol. 98, pp. 778–787, Jul. 2016.

[203] J. Taha-Tijerina, N. Cadena-De La Peña, R. Cue-Sampedro, and C. Rivera-Solorio, "Thermo-physical evaluation of dielectric mineral oil-based nitride and oxide nanofluids for thermal transport applications," *J. Thermal Sci. Technol.*, vol. 14, no. 1, 2019, Art. no. JTST0007.

[204] M. M. Ghislain, O. B. Gerard, T. N. Emeric, and M. I. Adolphe, "Improvement of environmental characteristics of natural monoesters for use as insulating liquid in power transformers," *Environ. Technol. Innov.*, vol. 27, Aug. 2022, Art. no. 102784.

[205] X. Peng, Q. Wang, S. Kang, C. Chen, G. Li, K. Wang, R. Liao, and X. Zhao, "Research progress in modified mineral oil, natural ester and mixed oil in transformers," *Electr. Mater. Appl.*, vol. 1, no. 1, Apr. 2024, Art. no. e12005.

[206] N. Ainanie Azizie and N. Hussin, "Preparation of vegetable oil-based nanofluid and studies on its insulating property: A review," *J. Phys., Conf. Ser.*, vol. 1432, no. 1, Jan. 2020, Art. no. 012025.

[207] M. M. Ghislain, A. Jean-Bernard, and M. I. Adolphe, "Effect of FeO_3 nanoparticles on the thermodynamic and physico-chemical properties of nanofluid based on kernel palm oil methyl ester (KPOME)," *Fuel Commun.*, vol. 12, Sep. 2022, Art. no. 100076.

[208] H. Pourpasha, S. Zeinali Heris, R. Javadpour, M. Mohammadpourfard, and Y. Li, "Experimental investigation of zinc ferrite/insulation oil nanofluid natural convection heat transfer, AC dielectric breakdown voltage, and thermophysical properties," *Sci. Rep.*, vol. 14, no. 1, p. 20721, Sep. 2024.

[209] S. S. M. Ghoneim, S. S. Dessouky, I. B. M. Taha, M. Shaaban, and S. A. M. Abdelwahab, "A new approach of tap changer maintenance incorporating nanoparticle insulating oil," *Electr. Eng.*, vol. 103, no. 2, pp. 931–944, Apr. 2021.

[210] N. Rajda and R. R. Patel, "Characterization of virgin and aged transformer oil with SiO_2 nanoparticles," in *Proc. Innov. Power Adv. Comput. Technol. (i-PACT)*, Apr. 2017, pp. 1–4.

[211] N. Baruah, M. Maharana, and S. K. Nayak, "Performance analysis of vegetable oil-based nanofluids used in transformers," *IET Sci., Meas. Technol.*, vol. 13, no. 7, pp. 995–1002, Sep. 2019.

[212] S. Sumathi and R. Rajesh, "Improvement on the characteristics of transformer oil using nanofluids," *Current Sci.*, vol. 118, no. 1, pp. 29–33, Apr. 2020. [Online]. Available: https://www.jstor.org/stable/27138632

[213] M. Maharana, M. M. Bordeori, S. K. Nayak, and N. Sahoo, "Nanofluid-based transformer oil: Effect of ageing on thermal, electrical and physicochemical properties," *IET Sci., Meas. Technol.*, vol. 12, no. 7, pp. 878–885, Oct. 2018.

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