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Review

From Mineral Oil to Dielectric Nanofluids: Review on Breakthroughs, Bottlenecks, and the Road to Commercialization

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Abstract

Power transformers are critical components of electric power infrastructure, and their liquid insulation systems are decisive for operational safety, reliability, and longevity. Conventional insulating fluids, particularly mineral oil, face increasing scrutiny due to low biodegradability, poor thermal performance, and non-renewable origin. Insulating oil-based nanofluids, engineered by dispersing nanoparticles (1–100 nm) into base oils, have emerged as transformative candidates for next-generation transformer liquid insulation. This review provides a comprehensive and critically integrated analysis of insulating oil-based nanofluids, systematically covering historical development, synthesis methodologies, colloidal stabilization strategies, and multi-technique characterization approaches. Dielectric performance metrics, including AC, DC, lightning-impulse breakdown voltages, partial-discharge inception voltage, and dielectric loss, are critically reviewed alongside thermal-conductivity enhancements and the thermo-viscous trade-off. Experimental evidence demonstrates that optimally formulated nanofluids enhance AC breakdown voltage by 20–60%, improve thermal conductivity by 10–40%, and significantly elevate partial discharge inception voltage depending upon various factors such as doping concentration, dispersion quality, moisture content, particle size/morphology, nanoparticle-oil system compatibility, etc. However, long-term colloidal instability, nanoparticle migration, compatibility with ageing products, and absence of standardized testing protocols continue to impede industrial deployment. This review identifies key research gaps and outlines a roadmap toward reliable, sustainable, and commercially viable insulating nanofluids for power transformer applications.

Keywords: dielectric nanofluids; dielectric strength; thermal stability; transformer cooling; liquid insulation advancements; insulating oil-based nanofluids; nanoparticle dispersion

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Academic Editor: Adolfo Dannier

Received: 10 June 2026
Revised: 25 July 2026
Accepted: 29 July 2026
Published: 3 August 2026

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1. Introduction

The rapid expansion of the global population, projected to reach approximately 9.7 billion by 2050, combined with accelerating industrialization and urbanization, is driving an unprecedented surge in global electricity demand and placing immense and growing pressure on existing electric power infrastructure [1,2]. At the heart of this infrastructure lies the power transformer as one of the most critical, irreplaceable, and capital-intensive components of any electric power system, responsible for stepping voltage up and down to enable the efficient

transmission and distribution of electricity from generation sources to end consumers [3,4]. Given this central role, any disruption in transformer operation can cascade into widespread power outages, significant economic losses, and serious threats to public safety and grid stability.

The reliable operation of a power transformer is fundamentally governed by the performance and integrity of its liquid insulation system, which simultaneously serves as a dielectric medium and a heat-dissipating coolant [5,6]. Statistical data from global utility surveys indicate that the average service life of a power transformer is approximately 40 years (range: 32–55 years); however, premature insulation degradation can reduce this to as little as 17.8 years, roughly half the expected operational life, resulting in premature asset retirement and substantial replacement costs [7,8]. More critically, approximately 75% of all transformer failures are directly attributable to insulation system degradation [9], with severe consequences, including catastrophic fires, toxic fluid spillage, environmental contamination, and costly unplanned outages. The economic toll of a single large transformer failure can range from several hundred thousand to over ten million US dollars [10,11]. Compounding this, the average operational lifespan of insulating oil itself is approximately 20 years under normal conditions, yet insulation degradation reduces this to as little as 5.5 years in practice, merely one-quarter of its expected service life [12], underscoring the inextricable link between insulating fluid quality and overall transformer longevity [13,14].

Among the available liquid insulation options, mineral oil has historically dominated the transformer insulation industry, owing to its well-established dielectric properties, low cost, good thermal conductivity, and decades of proven industrial performance. Nevertheless, mineral oil faces increasing scrutiny for its low biodegradability, relatively low flash point (140–160 °C), susceptibility to oxidative degradation, moisture sensitivity, and non-renewable, petroleum-based origin, all of which conflict with global sustainability and decarbonization targets [15–18]. In response, ester-based oils, both natural and synthetic, have emerged as the most viable alternatives. Natural esters, derived from vegetable sources such as soybean, sunflower, and rapeseed oils (e.g., FR3 by Cargill and BIOTEMP by ABB), offer exceptional biodegradability (>95% in 28 days), inherent non-toxicity, and a significantly elevated fire point (>300 °C) [18–20]. Synthetic esters, such as MIDEL 7131 and MIDEL eN, deliver superior oxidation resistance and a wide operational temperature range. However, both ester categories suffer from higher dielectric loss (tan δ), elevated viscosity at low temperatures, reduced volume resistivity, and higher procurement costs, limiting their large-scale industrial adoption [21,22].

These technical limitations of both mineral oil and ester-based alternatives, including suboptimal dielectric strength, thermal conductivity, and the fundamental trade-off between environmental compatibility and overall electrical performance in power transformers, collectively define a performance gap that no single conventional insulating fluid has been able to push the boundaries [23]. The emergence of nanotechnology has opened a transformative pathway to overcome these limitations. The foundational concept of nanofluids, engineered colloidal suspensions of nanoscale particles (typically 1–100 nm) in a base fluid, was formally introduced by Choi and Eastman in 1995 [24], who demonstrated remarkable thermal conductivity enhancements far exceeding classical theoretical predictions. Building on this, researchers began dispersing dielectric nanoparticles in conventional insulating oils to simultaneously enhance the electrical, dielectric, and thermophysical performance of the oils [25,26]. Experimental evidence has since demonstrated that optimally formulated insulating nanofluids can enhance the dielectric breakdown voltage (BDV) by 40–60% and elevate the partial discharge inception voltage (PDIV), depending on nanoparticle type, concentration, and size [27,28]. Nano-additives have also been shown to improve thermal conductivity, flash point, fire point, and pour point [29], while certain metal oxide nanoparticles, such as TiO_2, Al_2O_3, Fe_3O_4, and SiO_2, enhance oxidation stability and interfacial tension [4,30–32].

Furthermore, carbon-based nanomaterials, including graphene oxide (GO) [33,34], carbon nanotubes (CNTs) [28,35], and fullerene (C_{60}) [36,37], as well as hybrid nano-additives [38–40], combining multiple functional components, have attracted growing research interest due to their exceptional intrinsic thermal and electrical properties.

Despite these promising advances, several critical challenges continue to impede the large-scale commercialization of insulating nanofluids. Nanoparticle agglomeration and sedimentation, driven by strong van der Waals attractive forces and electrostatic interactions, lead to colloidal instability that degrades the very electrical and dielectric properties the nanofluid was designed to enhance [41]. Furthermore, nanoparticle addition beyond a critical concentration threshold leads to an undesirable increase in dynamic viscosity, thereby impairing convective heat transfer and partially offsetting the thermal benefits [8]. The effective thermal conductivity enhancement is further governed not only by the intrinsic properties of the nano-additive, but also by particle size, morphology, volume fraction, dispersion quality, and interfacial thermal resistance, all of which demand careful optimization [7].

Several review articles have previously addressed aspects of insulating oil-based nanofluids, including reviews focused on dielectric properties [42], thermal performance [23], stability [43], and physicochemical properties [44]. However, these existing reviews share a common agenda: they predominantly focus on single or a few property categories rather than providing an integrated multi-property analysis. However, this review article provides a comprehensive assessment of industrial deployment barriers that spans technological, economic, and regulatory dimensions simultaneously. The present review addresses these gaps by providing the multi-dimensional analysis of insulating oil-based nanofluids that spans the complete development pipeline, from fundamental synthesis chemistry and stabilization mechanisms, through multi-technique characterization and comprehensive property evaluation, to a rigorous assessment of industrial viability, while explicitly identifying and analyzing the contradictions, limitations, and unresolved questions that must be addressed before next-generation insulating nanofluids can transition from laboratory to industrial reality for their application in power transformer systems. The role, limitations, and evolution of liquid insulation in power transformers are illustrated in Figure 1.

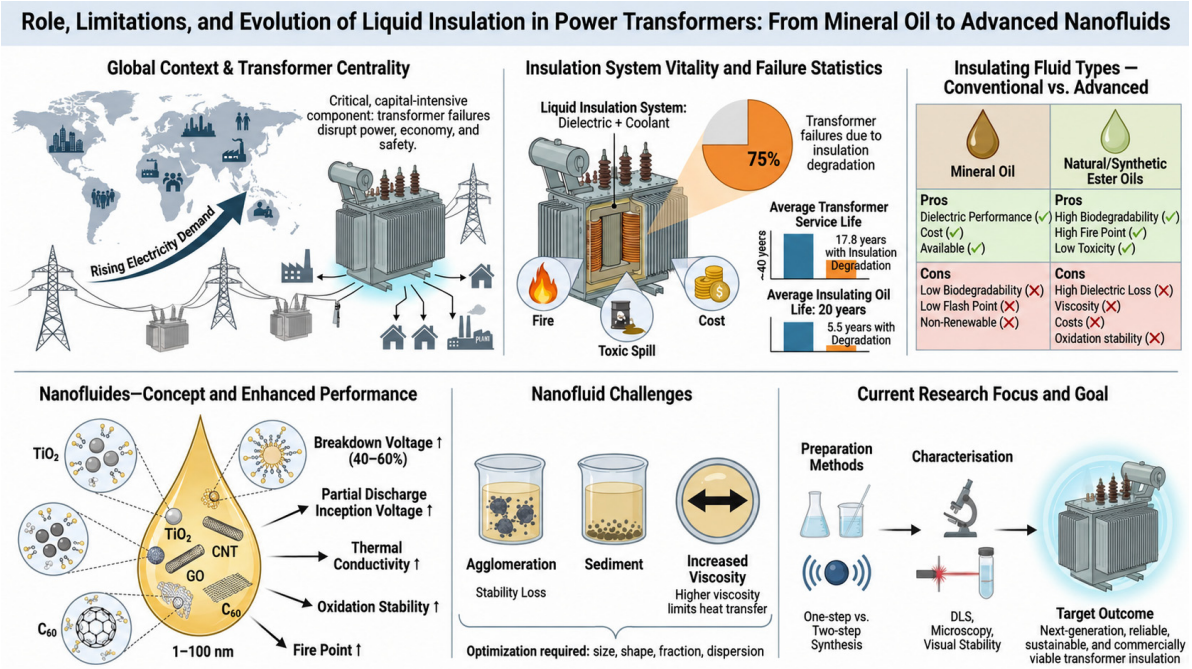


Figure 1. An overview of the role, limitations, and evolution of liquid insulation in power transformers.

2. Overview of Insulating Oil-Based Nanofluids

Insulating oil-based nanofluids are a novel class of engineered dielectric fluids, formally defined as stable colloidal suspensions of solid nanoscale particles (1 to 100 nm), dispersed in a conventional dielectric base oil, such as mineral oil, natural ester, or synthetic ester, with or without surface functionalization agents or chemical surfactants [45]. These nanofluids uniquely inherit the combined physicochemical attributes of both the solid nano-additive phase and the liquid base oil, resulting in a hybrid system whose collective dielectric, thermal, and physicochemical performance substantially exceeds that of either constituent alone. Their importance stems from their demonstrated ability to simultaneously enhance breakdown voltage (BDV), elevate partial discharge inception voltage (PDIV), improve thermal conductivity, and raise flash and fire points, all critical parameters governing transformer safety, efficiency, and longevity [46–48]. Consequently, insulating oil-based nanofluids are widely regarded as the most promising candidates for next-generation liquid insulation in power transformer systems.

History and Development of Insulating Oil-Based Nanofluids

The foundational breakthrough came in 1995, when Choi and Eastman formally introduced the concept of "nanofluids", engineered colloidal suspensions of nanoscale particles in a base liquid, demonstrating thermal conductivity enhancements far exceeding classical theoretical predictions [49]. Although initially focused on thermal transport, this pioneering work catalyzed the electrical engineering community to explore nanofluid concepts for transformer insulation. In 1998, Segal et al. conducted one of the first systematic electrical investigations, preparing a mineral oil-based nanofluid with dispersed magnetic Fe_3O_4 nanoparticles and reporting significant enhancements in lightning impulse breakdown voltage (30–40%) and partial discharge inception voltage (30%); however, AC dielectric breakdown strength remained close to the base oil [50]. This landmark study established the fundamental premise that nanoparticle dispersion could simultaneously improve multiple electrical performance metrics, while also identifying residual moisture in the base oil as a critical factor that negatively affects nanofluid dielectric performance. Subsequent investigations further explored the relationship between colloidal stability and dielectric performance. Kopčanský et al. (2003) studied oleic acid-coated magnetic nanoparticles in TECHNOL US 3000 insulating oil, revealing that externally applied magnetic fields induced nanoparticle aggregation through magnetic dipole–dipole interactions, and that the size and morphology of resulting aggregates critically governed dielectric strength [51]. Concurrently, Sartoratto et al. demonstrated that surface-coated magnetic nanoparticles at optimized concentrations yielded an AC dielectric strength enhancement of 12.86%, confirming that surface functionalization could effectively modulate nanofluid dielectric behavior [52]. Herchl et al. further investigated surface-modified magnetic nanoparticles in transformer oil under superimposed magnetic and high alternating electric fields of up to 14 MV/m, reporting concentration-dependent dielectric responses [53].

A critical theoretical advancement came in 2010, when Hwang et al. proposed the "trap theory" to explain the mechanism of dielectric strength improvement in nanofluids containing conductive nanoparticles [54]. This model postulates that negatively charged nanoparticle surfaces generate localized electric fields opposing the externally applied field, causing nanoparticles to act as electron traps that capture fast electrons, delay streamer propagation, and ultimately raise the dielectric breakdown threshold. This framework was further refined in 2012 by Du et al., who extended the concept to semiconductive nanoparticles through the "shallow trap theory" [55]. Using thermally stimulated depolarization current (TSDC) and pulse electroacoustic (PEA) techniques, Du et al. demonstrated that semiconductive nanoparticles significantly increase shallow trap density, enhancing charge

trapping and accelerating charge decay rates, collectively delaying streamer propagation and improving dielectric strength. The distinction between deep traps (conductive nanoparticles) and shallow traps (semiconductive nanoparticles) became a foundational principle for the rational design of insulating nanofluids [56].

Since the trap theory [54] and shallow trap theory [55,56] have provided the dominant mechanistic frameworks for dielectric enhancement in insulating nanofluids, a critical evaluation reveals important limitations that the field has not adequately addressed. The trap theory features dielectric enhancement in conductive nanoparticle systems through deep electron trapping on negatively charged nanoparticle surfaces, while the shallow trap theory extends this concept to semiconductive nanoparticles through reversible charge capture and accelerated charge decay. Both frameworks are well-supported experimentally for their respective nanoparticle types in mineral oil under AC conditions. However, neither theory can explain significant BDV enhancements reported for insulating nanoparticles (SiO_2, Al_2O_3, etc.), which possess no free electrons for conventional trapping and detrapping, suggesting that additional enhancement mechanisms, including interfacial polarization, streamer pathway modification, and space charge redistribution, operate independently [57,58]. The trap theory predicts a monotonic relationship between trap density and dielectric enhancement; however, experimental evidence shows a non-monotonic doping-concentration dependence, and the mechanism that deteriorates performance at high doping concentrations is not adequately explained by the trap model. Furthermore, both theories assume uniform nanoparticle distribution, ignoring agglomeration effects, and neither has been validated under DC voltage, impulse conditions, or in ester-based oil conditions, which is directly relevant to modern transformer applications. A unified theoretical framework integrating all contributing mechanisms, validated across diverse nanoparticle-oil systems and voltage conditions, remains a critical unresolved challenge for the field.

Following existing theoretical milestones in era, the field entered a phase of rapid diversification from 2013 onward, with researchers systematically exploring a broad spectrum of nano-additive types, including metal oxides (TiO_2 [59–61], Al_2O_3 [62–64], SiO_2 [65,66] Fe_3O_4 [32,67]), $Mn_{0.5}Zn_{0.5}Fe_2O_4$ [68], ZnO [69], ZrO_2 [70], CuO [71], sulfide, carbide and nitride based nanomaterials, CdS [7,72], SiC [73], and h-BN [74], carbon-based nanomaterials (graphene oxide [75–77] CNTs [78–80], fullerene C_{60}) [81–83], across diverse base oils including mineral oil, natural ester, and synthetic ester as well as blend oils. The period from 2018 to 2025 has been particularly productive, witnessing the emergence of hybrid nanofluid formulations, advanced surface functionalization strategies, and systematic studies on long-term aging behavior, substantially advancing the prospects for commercial deployment in operational power transformers [39,40,46]. The commonly used nano-additives in transformer oils are tabulated in Table 1. However, the history and development of insulating oil-based nanofluids are represented in Figure 2.

Table 1. The list of commonly used nano-additives in transformer oils.

Nanoparticle	Type	Base Oil	Doping Concentration Range	Key Enhancements	Ref.
TiO_2	Insulative	Canola-based oil	0.05–0.25 wt.%	AC Breakdown Voltage, Oxidation stability	[30]
Al_2O_3	Insulative	Naphthenic mineral oil	0.05–0.50 g/L	Breakdown voltage, Viscosity, Acidity/Flash point	[62]
Fe_3O_4	Magnetic	MIDEL 1204 (Natural ester oil)	0.05–0.4 g/L	DC Breakdown voltage	[84]

Table 1. *Cont.*

Nanoparticle	Type	Base Oil	Doping Concentration Range	Key Enhancements	Ref.
SiO_2	Insulative	MIDEL-7131, Mineral oil	0.05–0.4 g/L	AC Breakdown voltage	[85]
ZnO	Semi-conductive	Mineral oil	0.5–3.0 g/L	AC Breakdown Voltage	[69]
h-BN	Insulative	MIDEL-7131 (Synthetic ester oil)	0.025–0.1 g/L	AC Breakdown voltage, Thermal conductivity, Kinematic viscosity	[74]
ZrO_2	Insulative	Mineral, synthetic and natural ester oil.	0.1–0.5 g/L	AC Breakdown Voltage	[70]
CuO	Semi-conductive	Synthetic ester oil	0.01–0.04 wt.%	AC Breakdown voltage, Dissipation factor.	[86]
GO	Insulative	FR3 (Natural ester oil)	0.1–0.5 g/L	AC Breakdown voltage	[37]
MWCNT	Conductive	Used cooking oil methyl ester (UCOME)	0.02–0.10%	AC Breakdown voltage, Thermal conductivity/diffusivity, Viscosity,	[87]
C_{60}	Semi-conductive	Shell Diala S4 ZX-I	0.01–0.03% [w/v]	AC Breakdown voltage, Dissipation factor, Thermal conductivity	[81]
SiC	Semi-conductive	FR3 (Natural ester oil)	0.002–0.008% w/w	AC Breakdown voltage, Partial discharge, Dissipation factor,	[88]
CdS	Semi-conductive	MIDEL-7131 (Synthetic ester oil)	0.05–0.4 g/L	AC Breakdown voltage, Thermal stability	[7]
$Mn_{0.5}Zn_{0.5}Fe_2O_4$	Semi-conductive	Mineral oil	0.03–0.4 g/L	AC Breakdown Voltage, Dissipation factor, Thermal characteristics	[68]
Fe-Cu	Conductive	Rapeseed oil, Mineral oil, Synthetic ester oil	5–20 mg	AC Breakdown Voltage/Dissipation factor (Tan δ)	[89]

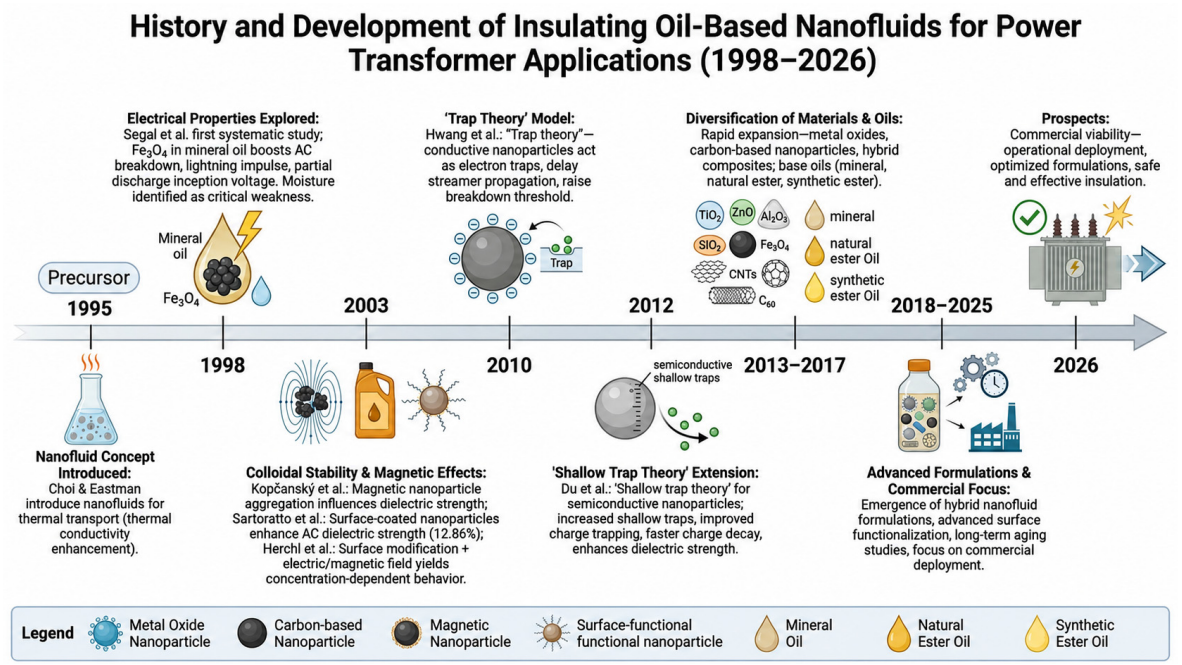


Figure 2. An overview of the history and development of insulating oil-based nanofluids over the years.

3. Synthesis of Dielectric Nanofluids

The preparation methodology employed in the synthesis of insulating oil-based nanofluids is not merely a procedural consideration; it is a critical determinant of nanofluid quality, colloidal stability, and ultimately improved electrical, dielectric, and thermal performance. Poorly prepared nanofluids, regardless of the intrinsic properties of their constituent nanoparticles, will inevitably suffer from agglomeration, sedimentation, and inconsistent dielectric behavior, rendering them unsuitable for transformer insulation applications [90–92]. The dispersion of nanoparticles in base fluids is quantitatively expressed in terms of volume fraction, volume concentration, mass fraction, or mass concentration as mixing representations, and the homogeneity of this distribution is paramount. Non-uniform particle size distribution is one of the most critical factors driving nanoparticle aggregation and subsequent performance degradation in nanofluids [93]. The preparation techniques reported in the literature are broadly classified into two principal approaches: the one-step method and the two-step method, each carrying distinct advantages, limitations, and suitability criteria for insulating nanofluid applications [94–96], as demonstrated in Figure 3.

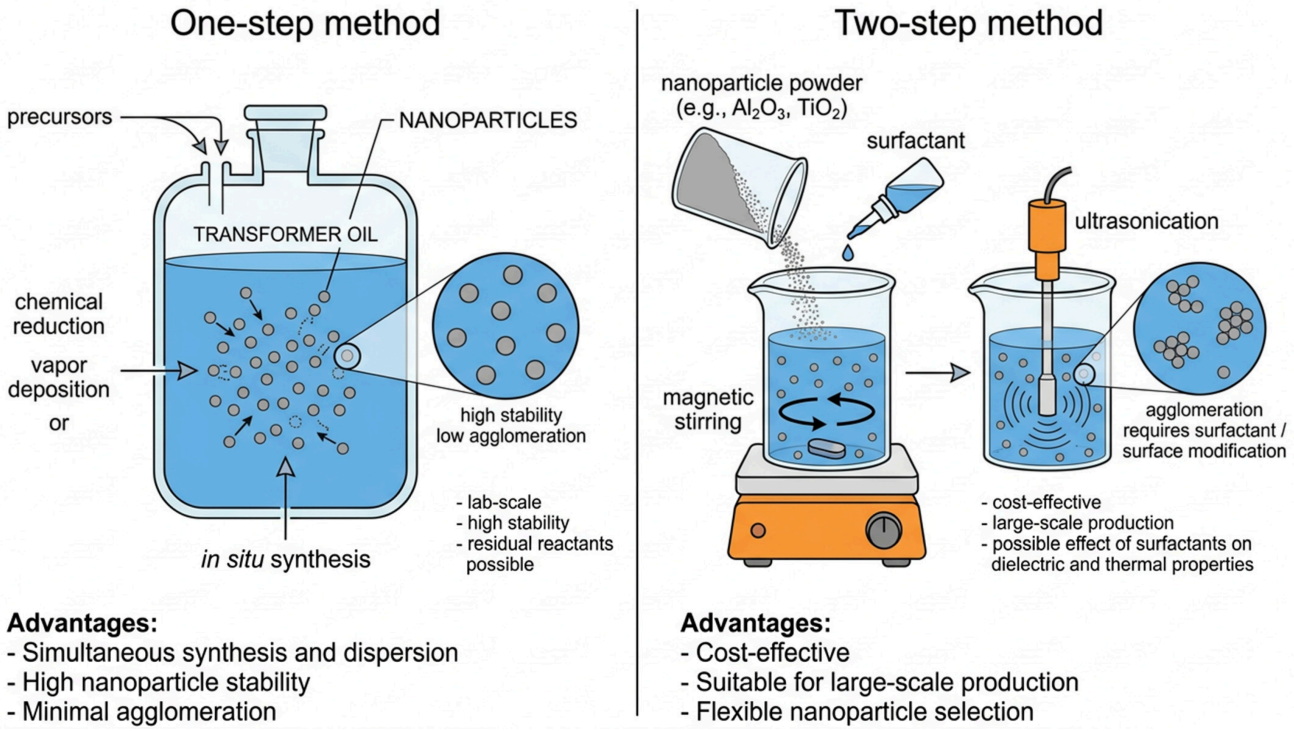


Figure 3. Illustration of one-step and two-step methods for the preparation of insulating oil-based nanofluids.

3.1. One-Step Method

In the one-step method, the synthesis of nanoparticles and their dispersion into the base insulating oil are performed simultaneously within a single integrated process, eliminating intermediate handling steps such as drying, storage, and re-dispersion that are known to promote agglomeration [90,92]. The most widely employed variant of this approach is based on physical vapour deposition (PVD), in which the nanoparticle precursor material is evaporated under controlled conditions and subsequently condensed directly into the base insulating oil, yielding a nanofluid in which the particles are finely dispersed from the moment of their formation [94]. Additional one-step variants reported in the literature include chemical vapour deposition (CVD), laser ablation, and submerged arc

nanoparticle synthesis (SANSS), each offering specific advantages in terms of particle size control and purity [95]. The primary advantage of the one-step method is the production of nanofluids with superior colloidal stability compared to the two-step counterpart, owing to the absence of intermediate steps. However, this method carries significant practical limitations that restrict its widespread adoption for transformer insulation applications. These include high equipment and operational costs, limited scalability for large-volume production, the potential introduction of chemical residuals into the nanofluid that may compromise dielectric properties, and its suitability being largely confined to base oils with low vapour pressure [92,94]. Consequently, while the one-step method remains scientifically valuable for laboratory-scale investigations and fundamental studies, it is not currently considered a viable route for industrial-scale production of transformer insulating nanofluids.

3.2. Two-Step Method

The two-step method is by far the most widely adopted preparation route for insulating oil-based nanofluids, and is considered the most practically viable approach for both research-scale and potentially industrial-scale production [97–99]. As the name implies, this method involves two distinct stages: (1) the independent synthesis of nanoparticles in powder form using established chemical or physical techniques such as sol–gel synthesis [69], arc-discharge [100], co-precipitation [46], microwave [101], solvothermal [7], hydrothermal processing [33], and ball milling [102]; followed by (2) the controlled dispersion of the pre-synthesized nanoparticles into the base insulating oil through a combination of mechanical and energy-intensive processing steps [103,104]. The dispersion stage typically involves an initial magnetic stirring phase to obtain a preliminary homogeneous mixture, followed by ultrasonication to break up nanoparticle agglomerated clusters and achieve a finer, more uniform dispersion. Two ultrasonication techniques are commonly employed: ultrasonic bath sonication and ultrasonic probe sonication. The latter is widely reported to be significantly more effective, as it delivers a higher localized energy density directly into the nanofluid sample, resulting in more efficient deagglomeration and superior particle dispersion [98,103]. Key sonication parameters, including duration, ultrasonic frequency, applied power, and processing temperature, critically influence the final dispersion quality and must be carefully optimized for each specific nanoparticle-oil system [105]. A drying step is also commonly incorporated to remove residual moisture from the nanoparticle powder prior to dispersion, as water content significantly deteriorates the dielectric properties of insulating nanofluids [97]. The practical implementation of the two-step method has been demonstrated across numerous studies. Dessouky et al. [106] employed an ultrasonic device operating for two hours to achieve uniform nanoparticle dispersion in insulating oil, incorporating infrared radiation to mitigate the formation of moisture bubbles and dissolved gases induced by ultrasonic processing, a practical innovation that addresses a commonly overlooked side effect of ultrasonication. Bhunia et al. [75] and Thabet et al. [107] utilized an AREC ceramic digital heating magnetic stirrer operating at approximately 550 °C and 1500 rpm to achieve initial dispersion, subsequently supplementing with ultrasonication to overcome the residual agglomerations that magnetic stirring alone could not resolve, a finding that underscores the complementary necessity of both techniques in the two-step process. While the two-step method offers significant advantages in flexible nanoparticle selection and straightforward nanofluid preparation. Yet, its primary challenge remains the tendency for nanoparticle re-agglomeration post-preparation, particularly during long-term storage [48,104]. Additionally, the two-step method faces significant scalability challenges, which are underreported in the literature. Batch-to-batch variability in nanoparticle dispersion quality, arising from inconsistencies

in ultrasonication energy, nanoparticle powder moisture content, and ambient temperature during nanofluid preparation, represents one of the major obstacles to reproducible large-scale production [108]. Prolonged ultrasonication, while effective for deagglomeration, carries significant energy costs; probe ultrasonication at typical power densities of 100–500 W/L for durations of 30–120 min results in substantial energy consumption [109]. Furthermore, ultrasonication-induced heating can alter the base oil chemistry and might damage the nanoparticle surface. It is essential to standardize quality control metrics, including minimum acceptable zeta potential and required stability duration, to pave the way from laboratory to industrial-scale production. These challenges motivate extensive research into standardized nanofluid preparation and stabilization strategies [108]. The ultrasonication parameters on different nano-additive/oil systems and their impact is illustrated in Table 2. However, the one-step and two-step methods are shown in Figure 3.

Table 2. Reported Sonication Parameters and Their Effects on Nanofluid Stability.

Base Oil	Nano-Additive	Doping Concentration	Sonication Type	Power (W)	Time (min)	Key Findings and Stability Outcome	Ref.
Nytro 4000X (MO) Bioelectra (NE)	Fe_3O_4	0.005–0.035	Probe	300	130	Visual observation Higher concentrations agglomerated in a few hours.	[110]
Transformer oil	$ZnFe_2O_4$ and TiO_2 doped MWCNT	0.1 wt%	Probe	70	45	Zeta potential values for all samples ranging from, Day 1 = −40.5 to −48.5 mV Day 16 = −32.6 to −36.2 mV	[111]
Mineral oil	$Mn_{0.5}Zn_{0.5}Fe_2O_4$	0.03–0.4 g/L	Probe	400	25	Zeta potential value of 8.73 proved moderate stability and positive charge on the surface of the nanoparticle	[68]
Mineral oil	CNTs	0.01–0.2 g/L	-	700	30–120	Samples with 120 min of sonication exhibited higher BDV than the samples with 30 min sonication time	[79]
Polyol ester oil	Al_2O_3	0.02 vol%	Bath	-	30–120	Reportedly, 80 min of sonication proved to be most stable with a zeta potential value of 45 mV after 10 days.	[112]
Disposed mineral oil	MWCNTs	0.00–0.02 g/L	Probe	700	120	Stable nanofluids exhibited enhanced electrical and thermal behaviour.	[80]
FR3	TiO_2	0.005–0.04 wt%	Bath		30	The nanofluids presented significant improvements in AC BDV, LI BDV and PD.	[113]
MIDEL-1204	ZnO	0.05–0.4 g/L	Probe	500	120	The stable nanofluids showed improved AC BDV	[114]
Transformer oil	ZrO_2	0.0015–0.0050 g/L			35–41	The sonication time was doping concentration dependent. The sonication time increased with increasing doping concentration.	[115]
Mineral oil and palm oil methyl ester	SiO_2 and graphene	0.01–0.10 wt%	Bath		300	The rate of sedimentation of nanoparticles in base oil was analysed via ultraviolet-visible spectrophotometer for 30 days. The computed R2 values gave insights into nanofluids' stability.	[116]

3.3. Homogeneous Dispersion and Colloidal Stability of Nanofluids

Achieving and maintaining long-term colloidal stability, defined as the sustained, homogeneous dispersion of nanoparticles within the base oil without agglomeration or sedimentation, is widely recognized as the most critical challenge in the development of application-ready insulating nanofluids [45,117,118]. The thermodynamic driving force for agglomeration arises from the interplay of van der Waals attractive forces, electrostatic interactions, gravitational settling, and buoyancy effects acting on nanoparticles at high surface-area-to-volume ratios [119]. The theoretical framework governing nanofluid stability is provided by the DLVO theory (Derjaguin, Landau, Verwey, and Overbeek) [120], which states that colloidal stability is determined by the balance between electrostatic double-layer repulsive forces and van der Waals attractive forces, a nanofluid is considered stable when repulsive forces sufficiently outweigh attractive forces, typically quantified by a zeta potential magnitude exceeding $\pm$30 mV [121]. Since the low dielectric constant of mineral oil ($\varepsilon_r \approx 2.2$) and natural ester ($\varepsilon_r \approx 3.2$) reduces the range and magnitude of electrostatic double layer repulsion compared to an aqueous system, the electrostatic stabilization alone is insufficient to maintain colloidal stability in dielectric nanofluids. In this non-polar medium, stabilization can be achieved more effectively through surface modification with long-chain organic molecules that create a physical barrier against particles [122].

To achieve this stability threshold, researchers have developed and validated several complementary stabilization strategies in addition to basic ultrasonication. Surface modification of nanoparticles, through functionalization with organic acids, silane coupling agents, or polymer coatings, is among the most effective approaches, as it introduces steric repulsion between particles and improves their compatibility with the non-polar base oil medium [123]. Oparanti et al. demonstrated this effectively by functionalizing nanoparticles with oleic acid, dispersing 5 g of nanoparticles in 100 mL of ethanol with 0.25 mL of oleic acid, stirring for 2 h, collecting by centrifugation, and drying at 80 °C, before dispersing the coated nanoparticles in palm kernel methyl ester. The oleic acid coating introduced intermolecular steric forces that physically separated nanoparticles, significantly reducing the tendency to agglomerate and improving dispersion quality [124].

The addition of chemical surfactants is another widely employed stabilization strategy, operating through steric and electrostatic mechanisms that render the inherently hydrophobic nanoparticle surfaces hydrophilic, thereby generating a surface charge that creates repulsive forces between suspended particles [125,126]. Surfactants are broadly classified as cationic, anionic, and nonionic (e.g., Span 80, Tween 80), with the selection of the most appropriate type being critical to stabilization efficacy and compatibility with the base oil system [127]. However, surfactant addition carries important caveats: at temperatures exceeding 60 °C, the surfactant-nanoparticle bond can thermally degrade, compromising stability under transformer operating temperatures [128]. Furthermore, surfactants have been reported to negatively affect the heat transfer capability of nanofluids and, in some formulations, adversely influence dielectric properties, necessitating careful optimization of surfactant type and concentration [129,130]. Nanofluid stability can be quantitatively assessed using zeta potential analysis, UV-Vis Spectrophotometry, dynamic light scattering (DLS), sedimentation observation, and electron microscopy, which collectively provide a comprehensive characterization of dispersion quality and long-term stability [131]. The nanofluid synthesis methods, stabilization strategies, and colloidal stability assessment are shown in Figure 4.

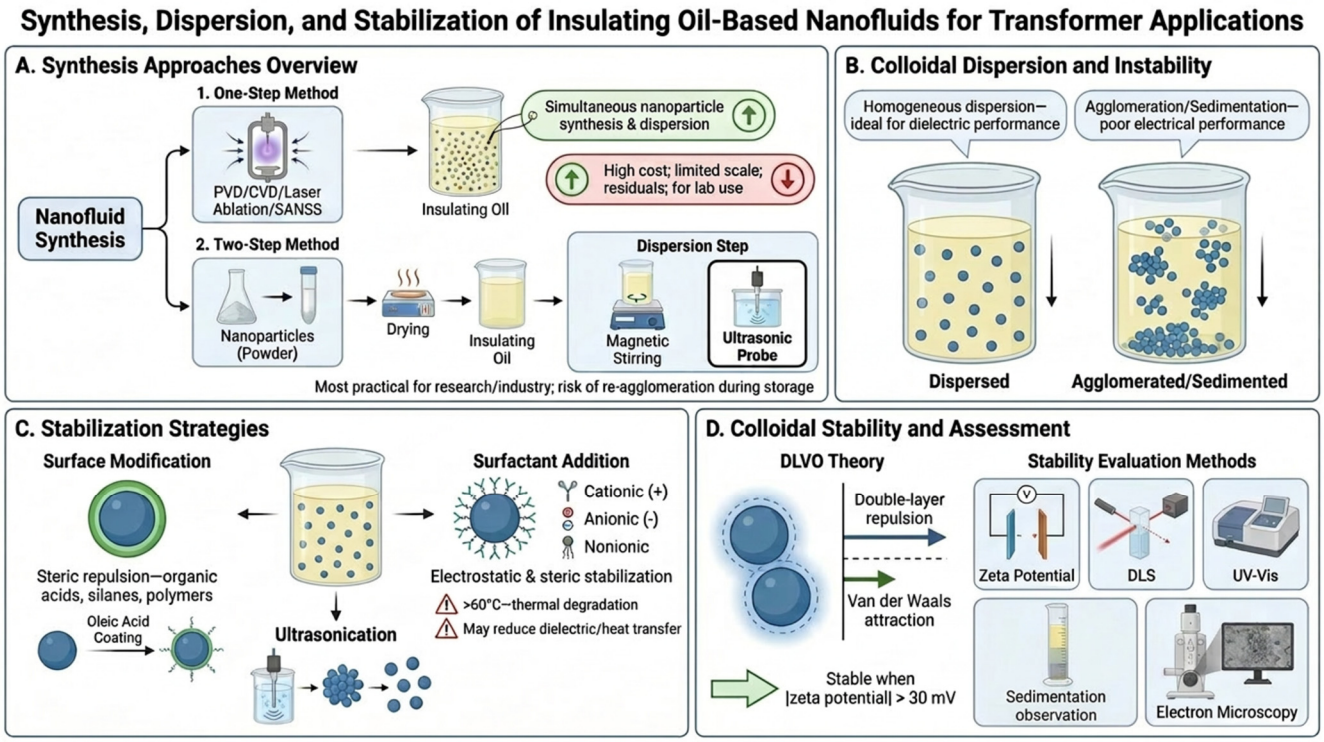


Figure 4. Nanofluid Synthesis methods, Stabilisation strategies, and colloidal stability assessment.

4. Characterization of Nanomaterials and Nanofluids

The characterization of insulating oil-based nanofluids is indispensable for bridging preparation methodology and performance evaluation. Comprehensive characterization not only confirms the structural integrity, phase purity, and surface chemistry of the dispersed nanoparticles, but also quantifies the degree of dispersion, colloidal stability, and charge transport behavior of the resulting nanofluid parameters that directly govern its electrical and dielectric performance in transformer applications [113]. Without rigorous characterization at each stage of preparation, it is impossible to establish reliable structure-property relationships or to diagnose the root causes of performance variability between studies. The characterization techniques employed in insulating nanofluid research can be logically organized into four progressive categories: (1) structural and morphological characterization, (2) surface chemistry characterization, (3) dispersion and colloidal stability characterization, and (4) electrical and computational characterization, as discussed below [132,133]. These categories are depicted in Figure 4.

4.1. Structural and Morphological Characterization

Scanning electron microscopy (SEM) is one of the most widely used techniques for investigating the microstructure, surface morphology, and particle-size distribution of nanoparticles and nanostructured materials used in insulating nanofluids. Operating by rastering a focused electron beam across the sample surface and detecting secondary or backscattered electrons, SEM provides high-resolution topographical images at magnifications typically ranging from 20 to 100,000 times, enabling direct visualization of particle shape, surface texture, and agglomeration state. However, SEM lacks the ability to image individual particles if they are very small in size [134,135]. Transmission electron microscopy (TEM) offers significantly higher resolution than SEM, enabling imaging of individual nanoparticles at the atomic lattice level by detecting electrons transmitted through an ultrathin sample. Beyond morphological imaging, TEM enables

selected area electron diffraction (SAED) analysis, which provides direct confirmation of nanoparticle crystallinity and phase structure, information that is critical for correlating nanoparticle crystal quality with dielectric performance. Despite these advantages, TEM sample preparation requires ultra-thin sections that might not represent the bulk nanofluid dispersion state, and beam-induced damage might alter the nanoparticle structure during imaging [7,136]. X-ray diffraction (XRD) complements electron microscopy by providing bulk-averaged crystallographic information, enabling the identification of crystal phases, calculation of crystallite size via the Scherrer equation, and assessment of lattice strain and defect density in nanoparticle samples. However, the XRD requires a dry powder sample; thus, XRD cannot provide information about the crystallographic state of nanoparticles within the insulating oil medium [7]. Energy-dispersive X-ray Spectroscopy (EDX), typically performed in conjunction with SEM or TEM, provides elemental composition analysis of nanoparticles, confirming the presence of expected elements and detecting potential contaminants or surface coating species [137].

4.2. Surface Chemistry Characterization

Fourier transform infrared (FTIR) spectroscopy is the primary technique for investigating the surface chemistry and functional group composition of both nanoparticles and insulating oil-based nanofluids. By identifying characteristic infrared absorption bands associated with specific chemical bonds and functional groups, FTIR provides direct evidence of successful surface functionalization, confirming, for example, the attachment of oleic acid, silane coupling agents, or surfactant molecules to nanoparticle surfaces following modification treatments. This is particularly valuable for verifying that surface modification has been achieved without altering the chemical integrity of the base insulating oil [138]. Raman spectroscopy serves as a complementary surface characterisation tool, employing inelastic light scattering to detect the vibrational spectrum of nanoparticles with exceptional sensitivity to structural defects, crystalline disorder, and carbon-based nanomaterial quality, making it especially important for characterizing graphene oxide, carbon nanotubes, and fullerene C_{60} used in carbon-based insulating nanofluids [139]. Fluorescence spectroscopy provides additional information on the composition, concentration, and mass distribution of nanoparticle samples, and has been employed in select studies to monitor nanoparticle behavior within insulating oil matrices [140,141].

4.3. Dispersion and Colloidal Stability Characterization

The quantification of nanoparticle dispersion quality and long-term colloidal stability is arguably the most practically important characterization dimension for insulating nanofluid applications. Dynamic light scattering (DLS) [142] is the most widely used technique for this purpose, measuring the hydrodynamic diameter of dispersed nanoparticles and the polydispersity index (PDI), a measure of particle-size distribution uniformity, by analyzing the time-dependent fluctuations in scattered laser light intensity caused by Brownian motion. DLS is particularly valuable for monitoring agglomeration over time, as an increase in the measured hydrodynamic diameter directly indicates progressive particle clustering [143]. Zeta potential analysis provides a complementary and quantitative measure of electrostatic colloidal stability, reflecting the magnitude of the surface charge on dispersed nanoparticles. According to established colloidal science principles and DLVO theory, a zeta potential magnitude exceeding ± 30 mV is the widely accepted threshold for a colloidally stable nanofluid, while values below this threshold indicate increasing susceptibility to agglomeration

and sedimentation [62,65]. Zeta potential is sensitive to pH, ionic strength, and surfactant concentration, and its systematic measurement as a function of these parameters provides critical guidance for optimizing stabilization strategies [140]. Despite the critical importance of DLS and Zeta potential characterizations in establishing reliable structure-property relationships for insulating nanofluids, the field currently requires standardized characterization protocols analogous to those available for dielectric testing (IEC 60156:2025 [144]; IEC 60897:1987 [145]). This is because DLS is highly sensitive to the presence of large aggregates, which can dominate the scattering signal and mask the true size distribution of well-dispersed particles. It also cannot distinguish between individual particles and stable small aggregates. However, Zeta potential measurements in low-permittivity non-aqueous media (mineral oil, $\varepsilon_r \approx 2.2$) are subject to significant uncertainty, as the classical electrokinetic models underlying zeta potential calculation were developed for aqueous systems and may not accurately describe charge behaviour in non-polar oils. This lack of standardized characterization protocols contributes directly to the inter-study variability in reported performance data and makes reliable cross-study comparison extremely difficult. The development of standardized characterization guidelines for insulating nanofluids, potentially within the IEC or ASTM standardization framework, represents an urgent priority for the field. Additionally, optical microscopy (OM) offers a direct visual assessment of the nanoparticle dispersion state at the microscale, enabling qualitative observation of agglomerate formation and sedimentation behavior over time [146].

4.4. Electrical and Computational Characterization

Beyond structural and stability characterization, a suite of specialized electrical and computational techniques is employed to probe the charge-transport dynamics and dielectric behavior of insulating nanofluids, properties that are directly relevant to transformer insulation performance. Thermally stimulated current (TSC) analysis is used to determine trap energy levels and trap density within the nanofluid, providing experimental validation of trap theory and mechanisms underlying shallow-trap theory [56]. By measuring the thermally activated release of trapped charges as a function of temperature, TSC reveals the depth and density of charge traps introduced by nanoparticle incorporation, information that is essential for understanding the mechanistic basis of dielectric strength enhancement [8]. The pulse electroacoustic (PEA) technique complements TSC by enabling direct measurement of space charge distribution and charge carrier transport characteristics within insulating liquids under applied electric fields, providing dynamic insight into how nanoparticles influence charge injection, migration, and accumulation, all of which are critical determinants of dielectric breakdown behavior [56]. Finite element analysis (FEA), as a computational simulation approach rather than an experimental technique, is employed to model the electric potential distribution, displacement field, and current density distribution within nanofluid systems as a function of nanoparticle properties and concentration, providing theoretical predictions that complement and guide experimental characterization efforts [147]. Comprehensive characterizations of insulating oil-based nanofluids are shown in Figure 5.

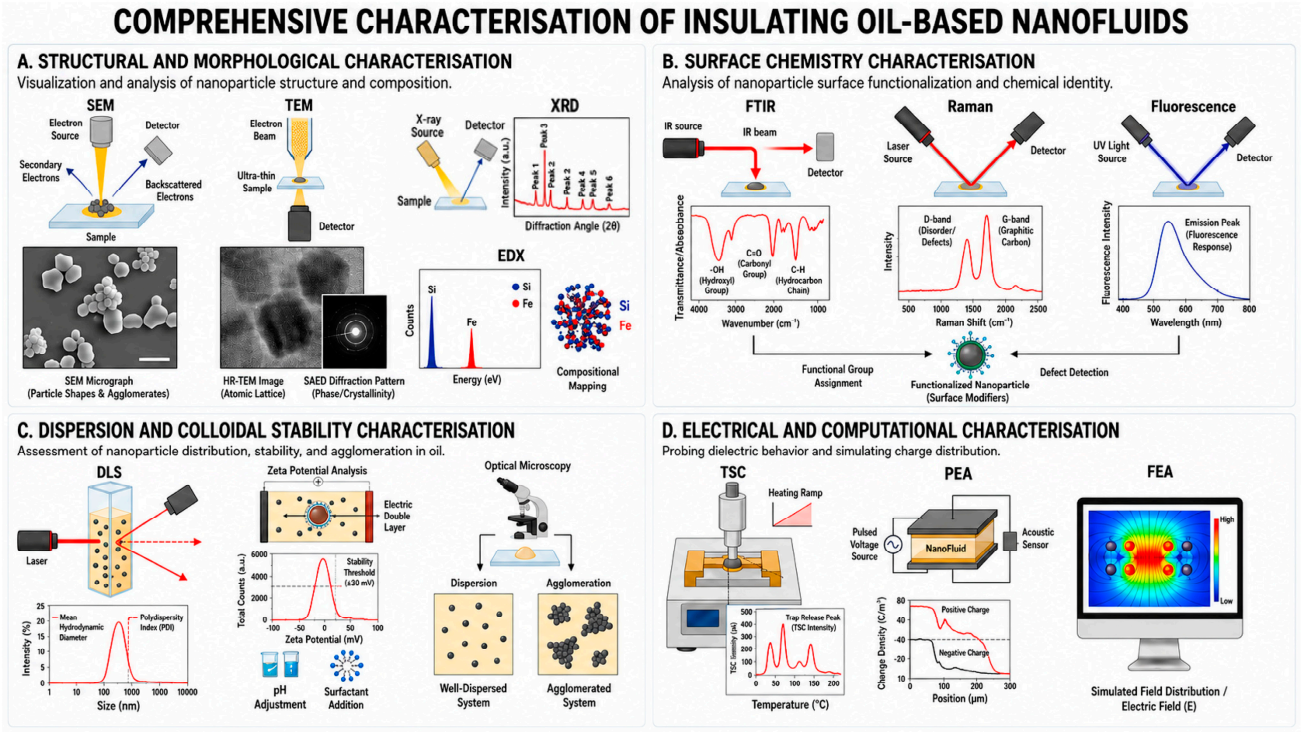


Figure 5. A comprehensive characterisation framework for nanomaterials and nanofluids: (**A**) Structural and morphological; (**B**) Surface chemistry; (**C**) Colloidal stability; and (**D**) Electrical, thermal and computational characterisation techniques.

5. Dielectric, Electrical, and Thermal Properties of Nanofluids

The performance of insulating oil-based nanofluids in power transformer applications is evaluated across two fundamental and deeply interconnected property categories: dielectric and electrical properties, which determine the nanofluid's ability to withstand high electric fields and suppress discharge phenomena, and thermal properties, which govern the fluid's capacity to dissipate heat generated in transformer windings and core. The introduction of nanoparticles into insulating base oils simultaneously modifies both categories through complex multiphase interactions between the base fluid, nanoparticles, and applied electric field, whose outcomes are critically sensitive to nanoparticle type, concentration, particle size, particle morphology, surface chemistry, and dispersion quality [7,8,22]. The following subsections provide a critically integrated and progressive analysis of each key performance metric.

5.1. Dielectric Loss (tan δ)

Dielectric loss, expressed as the loss tangent (tan δ), quantifies the electrical energy dissipated as heat within a dielectric material under specific conditions of frequency, temperature, and applied voltage [148]. It serves as one of the most sensitive indicators of insulating oil quality. Elevated tan δ values directly signal the presence of impurities, moisture, ionic contaminants, or oxidative degradation products within the fluid [149]. In electrical insulation systems, dielectric loss arises from two primary mechanisms: ionic conduction and polarization losses. Non-polar mineral oil experiences dielectric loss exclusively through conduction, while polar fluids such as methyl ester incur losses through both mechanisms due to their molecular polarity [150]. The total dissipation factor is expressed as:

$$tan\delta = \frac{k}{\varepsilon_0 \varepsilon_r \omega} = tan\delta_P + tan\varepsilon_G \quad (1)$$

where κ is the electrical conductivity, ε_0 is the dielectric constant, $\omega = 2\pi f$ is the angular frequency, ε_r is the relative permittivity, Tan δ_P represents the dissipation factor resulting from polarization losses, and tan ε_G represents the dissipation factor resulting from conduction losses [44].

Experimental evidence consistently demonstrates that dielectric nanoparticles at optimized concentrations significantly reduce tan δ. Oparanti et al. [124] studied methyl ester nanofluids with Al_2O_3 and TiO_2 at 0.2–1.0 wt% (60 Hz), finding that while purified methyl ester showed an increase in dielectric loss relative to palm kernel oil, due to chemical dissociation during transesterification. However, Al_2O_3 and TiO_2 nanofluids reduced dielectric loss by 79.9% and 58.2%, respectively, at an optimum of 0.6 wt%. In a follow-up study [151], the same group confirmed reductions of 97% (Al_2O_3) and 94% (TiO_2) at 0.6 wt% at 30 °C. Tambuwal et al. [152] reported reductions of 96.2% and 91.5% in jatropha and neem TiO_2 nanofluids at 1 wt%. Conversely, Khan et al. [89] observed that magnetic Fe-Cu and Fe_3O_4 nanoparticles increased the dissipation factor in both rapeseed and synthetic ester oils by forming conductive chains that facilitated ionic conduction, while TiO_2 uniquely reduced it, reinforcing the critical role of nanoparticle electrical conductivity type in determining dielectric loss behavior.

The underlying mechanism is governed by electron capture: upon application of an electric field, nanoparticles become polarized, generating surface charges aligned with the field. Free electrons produced through ionization are rapidly captured by positively charged nanoparticle surfaces, neutralizing surface charges and redistributing charge across the nanoparticle. This reduces free charge density, suppresses streamer formation, and decreases ionic conduction, collectively lowering tan δ [54]. Once all nanoparticles reach charging saturation and become negatively charged, electron capture ceases, defining the upper concentration threshold beyond which further nanoparticle addition no longer reduces dielectric loss [153].

5.2. AC Breakdown Voltage (AC BDV)

AC breakdown voltage (BDV) is the most extensively studied electrical parameter in insulating nanofluid research, defined as the minimum AC voltage required to cause catastrophic dielectric failure. Testing follows IEC 60156, which specifies a 2.5 mm electrode gap and a voltage rise rate of 2.5 kV/s [4,91]. Multiple factors critically govern the performance of AC BDV in nanofluids.

Water content significantly reduces AC BDV by forming multimolecular clusters that distort the local electric field. Studies on Fe_3O_4-mineral oil nanofluids demonstrated that while water content reduced BDV in both bare oil and nanofluids, nanofluids exhibited significantly lower sensitivity to moisture, attributed to nanoparticle surface adsorption breaking up water clusters into individual molecules, reducing their field-distortion effect [74,154–157]. TiO_2 nanofluids similarly outperformed bare mineral oil at elevated water contents, with TiO_2 nanoparticles reducing water-induced distortion of the electric field [50,158].

Nanoparticle size governs AC BDV through its effect on specific surface area: smaller particles possess larger surface-area-to-volume ratios, enabling greater charge accumulation at the liquid-solid interface, more effective electron trapping, and consequently delayed streamer propagation [85,159]. Morphology further amplifies this effect: Bhunia et al. [129] reported 27–30% AC BDV enhancement using 2D anatase TiO_2 nanosheets, attributed to their large surface area, high phonon mean free path, and surface oxygen vacancies. Lv et al. [160] demonstrated that TiO_2 nanorod nanofluids achieved a 55% higher breakdown strength than base oil and 1.23× higher positive impulse BDV than TiO_2 nanosphere nanofluids, attributed to reduced electric field distortion. Xu et al. [161] showed that

1D and 2D Co_3O_4 nanomaterials undergo field-induced rearrangement, modifying trap depth levels and electric potential distribution, confirming that non-spherical morphologies generally outperform spherical nanoparticles in dielectric enhancement.

Doping concentration follows a well-established non-monotonic relationship with AC BDV: performance improves up to an optimal threshold, beyond which agglomeration and formation of conductive percolation pathways, enabling electron tunnelling between closely spaced nanoparticles, cause progressive BDV deterioration. Identifying this optimal concentration window is therefore essential for each specific nanofluid system [159].

5.3. DC Breakdown Voltage (DC BDV)

It is important to note that, there is no dedicated and universally adopted international standard specifically for DC breakdown voltage testing of dielectric liquids. Studies on DC BDV of dielectric liquids have generally employed modified IEC 60156 test apparatus under DC voltage conditions, without a formally standardized testing protocol. This absence of a dedicated DC BDV standard represents a significant gap in the standardization framework. The development of a dedicated IEC standard for DC breakdown voltage testing of insulating liquids, including dielectric nanofluids formulations, represents an urgent priority for the IEC Technical Committee.

Due to the absence of a standard DC BDV testing protocol, the research on insulating nanofluids under DC voltage has received comparatively little attention, yet represents an increasingly critical area given the rapid global expansion of HVDC transmission networks [154]. Beroual and Khaled systematically investigated Fe_3O_4, Al_2O_3, and SiO_2 nanoparticles in natural ester (MIDEL 1204) under DC voltage, employing Weibull and normal distribution statistical analysis. Fe_3O_4 (50 nm) at 0.3 g/L yielded the highest DC BDV enhancement of 10.6%, while Al_2O_3 (50 nm) and Al_2O_3 (13 nm) achieved 9% and 7.6% improvements at 0.3 g/L and 0.4 g/L, respectively. Notably, SiO_2 exhibited a continuous decrease in DC BDV with increasing concentration, attributed to its insulative nature and tendency to form charge-blocking agglomerates under DC fields, highlighting that nanoparticle behavior under DC conditions can differ substantially from AC behavior [84,155].

5.4. Lightning Impulse Breakdown Voltage (LI BDV)

Lightning impulse breakdown voltage (LI-BDV) evaluates the fluid's ability to withstand transient overvoltage from lightning strikes, tested at 1.2/50 µs in a needle-sphere configuration with a 25 mm gap as per IEC 60897 and ASTM D3300 [156,162]. Positive impulse BDV (representing 5% of lightning events but generating up to 1 billion volts) is generally lower and more critical for insulation design than negative impulse BDV [157].

The polarity (positive and negative impulse) dependence of LI BDV arises from fundamentally different streamer propagation mechanisms under each polarity. Under positive lightning impulse, fast-mode streamers propagate rapidly from the high-voltage needle electrode through a highly branched structure driven by electron avalanche multiplication in the high-field region ahead of the streamer tip, a propagation mode that is energetically favourable, develops at lower applied voltages, and produces the lower positive LI BDV values consistently observed experimentally. In contrast, under negative lightning impulse, slower, more filamentary streamers develop from the ground electrode, requiring significantly higher applied voltages to sustain propagation against the opposing field gradient, resulting in higher negative LIBDV values [156,157]. The presence of nanoparticles modifies these streamer dynamics through multiple complementary mechanisms, such as nanoparticles physically obstruct streamer channel growth by interrupting the continuous liquid phase through which streamers propagate; they modify the local electric

field distribution ahead of the streamer tip by introducing dielectric discontinuities at the nanoparticle-oil interface; and they provide charge trapping sites that reduce the electron avalanche multiplication rate, effects that are more pronounced for positive streamers due to their higher propagation velocity and greater sensitivity to local field perturbations [163].

Nanoparticle morphology and specific surface area, nanoparticle concentration, base oil type and polarity are the most important factors which affect the LI BDV. Non-spherical morphologies, including nanorods, nanosheets, and platelet structures, provide more effective streamer pathway obstruction and larger interfacial areas for charge redistribution than spherical nanoparticles of equivalent concentration. Lv et al. [160] demonstrated that TiO_2 nanorod nanofluids achieved 1.23 times higher positive impulse BDV than TiO_2 nanosphere nanofluids, attributed to the lower electric field distortion associated with elongated morphologies. The h-BN in cottonseed oil improved LI-BDV by 5% at 0.1 wt% [164], while h-BN in vegetable oil enhanced positive and negative LI-BDV by 23% and 10% at 0.1 vol% [165]. Fullerene (C_{60}) in ester oil yielded an 8.2% improvement at 0.1 g/L [166], and graphene oxide (GO) in natural ester achieved 17% enhancement at an ultra-low 0.005 g/L [163], demonstrating exceptional carbon nanomaterial efficiency at minimal loading, showing the dependence of nanoparticle concentration. TiO_2 in natural ester improved LI-BDV by 12.94% [113], while Fe_3O_4 in rapeseed oil yielded 37% and 12% positive and negative LI-BDV enhancements, respectively. Al_2O_3 and SiC in vegetable oil improved positive LI-BDV by 28.5% and 6%. Beroual and Khaled further confirmed that insulating SiO_2 and Al_2O_3 enhanced the negative LIBDV of MIDEL 1204 by 13% and 16.8%, while magnetic Fe_3O_4 achieved 7.5%, confirming that nanoparticle electrical conductivity type significantly governs impulse performance [167].

5.5. Partial Discharge Inception Voltage (PDIV)

Partial discharge inception voltage (PDIV), the minimum voltage at which sustained localized electrical discharges first occur, is a highly sensitive indicator of insulation quality and a critical predictor of long-term transformer reliability [168,169]. Partial discharge (PD) testing follows IEC 60270:2025 [170] (conventional electrical method) or unconventional methods, including acoustic emission, ultra-high frequency (UHF), and high-frequency current transformer (HFCT) detection, with hybrid combinations increasingly employed for comprehensive characterization [171,172].

Fe_2O_3 in palm oil achieved optimal PDIV improvement at 0.01 g/L, which then declined at higher concentrations due to particle-bridge formation, thereby facilitating charge flow [173]. CQD-SiO_2 nanoparticles in mineral oil at 0.05–0.1 wt% enhanced PDIV by 23%, attributed to the superior electron trapping capability of the carbon quantum dot coating [174]. Al_2O_3 with SDS surfactant enhanced PDIV of RBDPO, coconut oil, and mineral oil by 34%, 39.3%, and 27%, respectively [175]. Fe_3O_4 and TiO_2 in refined palm oil demonstrated progressive PDIV enhancement with increasing concentration [176], while combined electrical-acoustic PD measurement confirmed significant enhancement in both PD magnitude and pulse number compared to base oil [177].

Collectively, PDIV enhancement depends on doping concentration, particle size, specific surface area, band-gap energy, morphology, dielectric permittivity, and dispersion homogeneity. The role of nanoparticle bandgap energy is particularly significant. Wide-bandgap nanoparticles (h-BN: ~6 eV; Al_2O_3: ~8.8 eV; SiO_2: ~9 eV) suppress charge injection from electrodes by presenting a high energy barrier to electron transfer. However, narrow-bandgap nanoparticles (Fe_3O_4: ~0.1 eV; TiO_2 anatase: ~3.2 eV) facilitate controlled charge trapping through their accessible conduction band states. Furthermore, the surface chemistry modulates the PDIV through its effect on the nanoparticle-oil interfacial polarization layer. The hydroxyl groups on the surface of metal oxide nanoparticles create dipolar polar-

ization centers that redistribute the local electric field in high-stress regions, reducing the probability of partial discharge initiation. Nanoparticle morphology affects PDIV through its influence on the local electric field distribution: elongated morphologies (nanorods, nanowires) can either enhance or reduce local field concentration depending on their orientation relative to the applied field, creating a morphology-dependent PDIV response that is not captured by spherical nanoparticle models [178].

5.6. Thermal Conductivity and Thermo-Viscous Trade-Off

Beyond dielectric and electrical performance, another primary motivation for nanoparticle incorporation into insulating oils is the enhancement of thermal conductivity k_{nf}, which directly improves heat dissipation from transformer windings and reduces equipment operating temperature. Carbon-based nanostructures are the most effective thermal conductivity enhancers: single-walled carbon nanotubes (SWCNTs) exhibit intrinsic thermal conductivity of approximately 3000–6000 W/m·K and graphene approximately 5000 W/m·K, far exceeding metal oxide nanoparticles (TiO_2: ~8.4 W/m·K; Al_2O_3: ~40 W/m·K) and insulating base oils (~0.13–0.17 W/m·K). Experimentally reported thermal conductivity enhancements in insulating nanofluids typically range from 5% to 40%, depending on nanoparticle type, concentration, and base oil system [5].

However, thermal conductivity enhancement is invariably accompanied by a concurrent increase in dynamic viscosity μ_{nf}, creating a fundamental thermo-viscous trade-off that critically affects practical transformer cooling applicability [5,179–181]. From a fluid dynamics perspective, increased viscosity reduces the Reynolds number:

$$Re = \frac{\rho v D}{\mu_{nf}} \quad (2)$$

where ρ is fluid density, v is flow velocity, and D is the hydraulic diameter. Reduced Re shifts flow toward laminar conditions, less favorable for convective heat exchange, meaning the overall heat transfer coefficient, governed by $Nu = f(Re, Pr)$ may not improve proportionally with thermal conductivity and may even decrease under severe viscosity penalties [166,179]. The concentration-viscosity relationship is highly nonlinear, particularly at higher nanoparticle loadings where interparticle interactions and agglomeration become significant. Consequently, identifying an optimal concentration that balances thermal conductivity enhancement with acceptable rheological behavior is essential and requires a system-level optimization approach that simultaneously considers thermal, hydraulic, and stability constraints for real transformer deployment [181]. Integrated effects of nanoparticles on dielectric, electrical, and thermal properties of insulating nanofluids for power transformer applications are summarized in Figure 6. However, a comparative summary of key dielectric and thermal performance enhancements reported for insulating oil-based nanofluids is summarised in Table 3.

Table 3. Comparative Summary of Key Dielectric and Thermal Performance Enhancements Reported for Insulating Oil-Based Nanofluids.

Nanoparticle	Base Oil	Optimal Conc.	AC BDV	DC BDV	LI BDV	Thermal Conductivity (TC)	Ref.
TiO_2	FR3	0.004% w/w			5.6%	25%	[88]
SiC	FR3	0.004% w/w			9.8%	58%	
Al_2O_3	MIDEL-7131 (SE) MIDEL-1204 (NE)	AC BDV @ 0.05 g/L (SE) DC BDV @ 0.3 g/L (NE) LI BDV @ 0.05 g/L (NE)	35%	7.6%	16.8%	-	[84,182,183]

Table 3. *Cont.*

Nanoparticle	Base Oil	Optimal Conc.	AC BDV	DC BDV	LI BDV	Thermal Conductivity (TC)	Ref.
Fe_3O_4	MIDEL-713 (SE) MIDEL-1204 (NE)	AC BDV @ 0.4 g/L (SE) DC BDV @ 0.2 g/L (NE) LI BDV @ 0.05 g/L (SE)	48%	10.6%	25.6%	-	[84,182,183]
SiO_2	MIDEL-713 (SE) MIDEL-1204 (NE)	AC BDV @ 0.4 g/L (SE) DC BDV @ 0.05 g/L (NE) LI BDV @ 0.3 g/L (SE)	32%	−5.9%	18.7%	-	[84,182,183]
GO	TRANSOL Transformer oil	0.01 wt% 0.0025 wt%	40%	-	-	30%	[75]
h-BN	Transformer oil	AC BDV-PBN-950 °C @0.0100 wt% AC BDV-PBN-1050 °C @0.0075 wt% TC PBN-950 °C @0.0075 wt% TC PBN-1050 °C @0.0100 wt%	26% 39% - -	-	-	PBN-950 = 32.5% PBN-1050 = 28%	[184]
MWCNT	Mineral Oil	0.005 g/L	212.5%		14.16%		[185]
C_{60}	Transformer oil	0.01% *w*/*v*	17%			2.3%	[82]
ZnO	Naphthenic base mineral	AC BDV @ 0.1 wt% TC @ 0.1 wt%	42.76%			81.83%	[186]

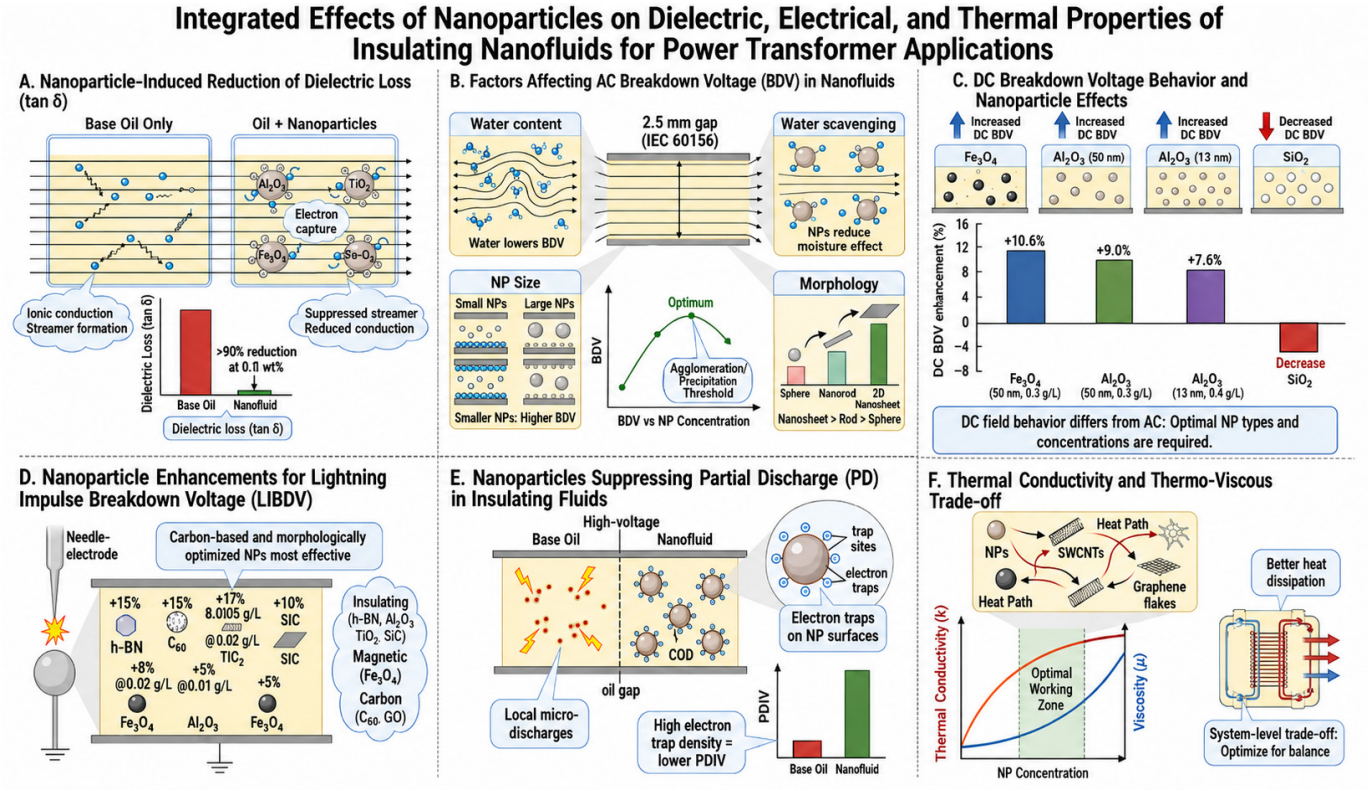


Figure 6. Integrated effects of nanoparticles on dielectric, electrical, and thermal properties of insulating nanofluids for power transformer applications: (**A**) Nanoparticle-induced reduction in dielectric loss (tan δ), (**B**) Factors affecting AC breakdown voltage (BDV) in nanofluids, (**C**) DC breakdown voltage behaviour, (**D**) Nanoparticle enhancements for LI BDV, (**E**) Nanoparticle suppressing PD in insulating fluids, (**F**) Thermal conductivity and thermo-viscous trade-off.

6. Analysis of Contradictions in the Literature

Despite the compelling body of experimental evidence supporting the potential of insulating oil-based nanofluids for power transformer applications, an honest and critical

reading of the literature reveals a landscape riddled with contradictions and inconsistencies that cannot be overlooked. These discrepancies stem from the inherent complexity of the physical phenomena governing nanofluid behaviour, the sheer diversity of nanoparticle systems investigated, and the striking variability in experimental protocols adopted across different research groups worldwide [187]. Perhaps the most intellectually intriguing of these contradictions is the paradoxical relationship between electrical conductivity and dielectric strength. Classical insulation theory dictates that any increase in electrical conductivity must be accompanied by a reduction in breakdown voltage, yet a growing body of experimental evidence demonstrates that nanoparticle addition can simultaneously raise both electrical conductivity and dielectric breakdown strength [163,188]. This behaviour is generally attributed to charge trapping at nanoparticle surfaces, whereby free electrons are captured before they can initiate electron avalanche processes, stabilising the local electric field distribution and delaying breakdown even as bulk conductivity marginally increases. What makes this contradiction even more challenging to resolve is its nanoparticle-type dependence: while conductive nanoparticles such as Fe_3O_4 and Ag exhibit this behaviour through well-established deep trapping mechanisms, insulative nanoparticles including SiO_2 and Al_2O_3, which theoretically lack the free electron density required for conventional charge trapping, also consistently report significant BDV enhancements, strongly implying that additional mechanisms such as interfacial polarisation and streamer pathway modification are operating independently. Neither the trap theory nor the shallow trap theory, as currently formulated, provides a satisfactory explanation for this observation [189]. A second area of genuine scientific disagreement concerns the influence of nanofluids on oil-paper insulation ageing. On one side of the debate, a substantial number of studies report that nanofluids improve the thermal stability of the insulation system by promoting more efficient heat dissipation and reducing the thermal stress experienced by cellulosic insulation [190–193]. On the other side, an equally credible body of evidence suggests that nanoparticles can interact with ageing by-products, including organic acids, furanic compounds, and carbon oxides, in ways that potentially catalyse oxidative or hydrolytic cellulose degradation reactions, thereby accelerating rather than retarding insulation ageing [194,195]. These conflicting findings are difficult to reconcile because the experimental conditions, nanoparticle chemical nature, concentration, base fluid type, and thermal ageing protocol differ so substantially between studies that direct comparison is essentially impossible. A third persistent contradiction involves the concentration dependence of dielectric performance. While low nanoparticle concentrations consistently enhance dielectric strength through charge trapping and field modification, exceeding a critical threshold triggers agglomeration and conductive pathway formation that progressively erodes the very properties the nanofluid was designed to improve [196,197]. The optimal concentration, at which dielectric enhancement peaks, typically falls between 0.005 wt% and 0.05 wt% across the literature, yet this range shifts considerably with nanoparticle type, size, surface chemistry, and base oil polarity, making it impossible to establish universal formulation guidelines from currently available data. Underlying all of these contradictions is a more fundamental problem: a substantial proportion of the inconsistencies observed across the literature are not the result of genuine physical differences between nanofluid systems, but rather reflect the profound methodological inconsistency that pervades the field [104,198]. Variability in preparation protocols, sonication parameters, surfactant use, electrode geometry, gap distance, moisture content, and thermal conditioning procedures, combined with the near-universal practice of conducting experiments in simplified laboratory test cells that bear little resemblance to the complex coupled thermal, electrical, and chemical environment of an operational power transformer, fundamentally limits the translational value of reported findings and makes the resolution of genuine scientific

contradictions extremely difficult. Contradictions and methodological inconsistencies in insulating oil-based nanofluids are illustrated in Figure 7.

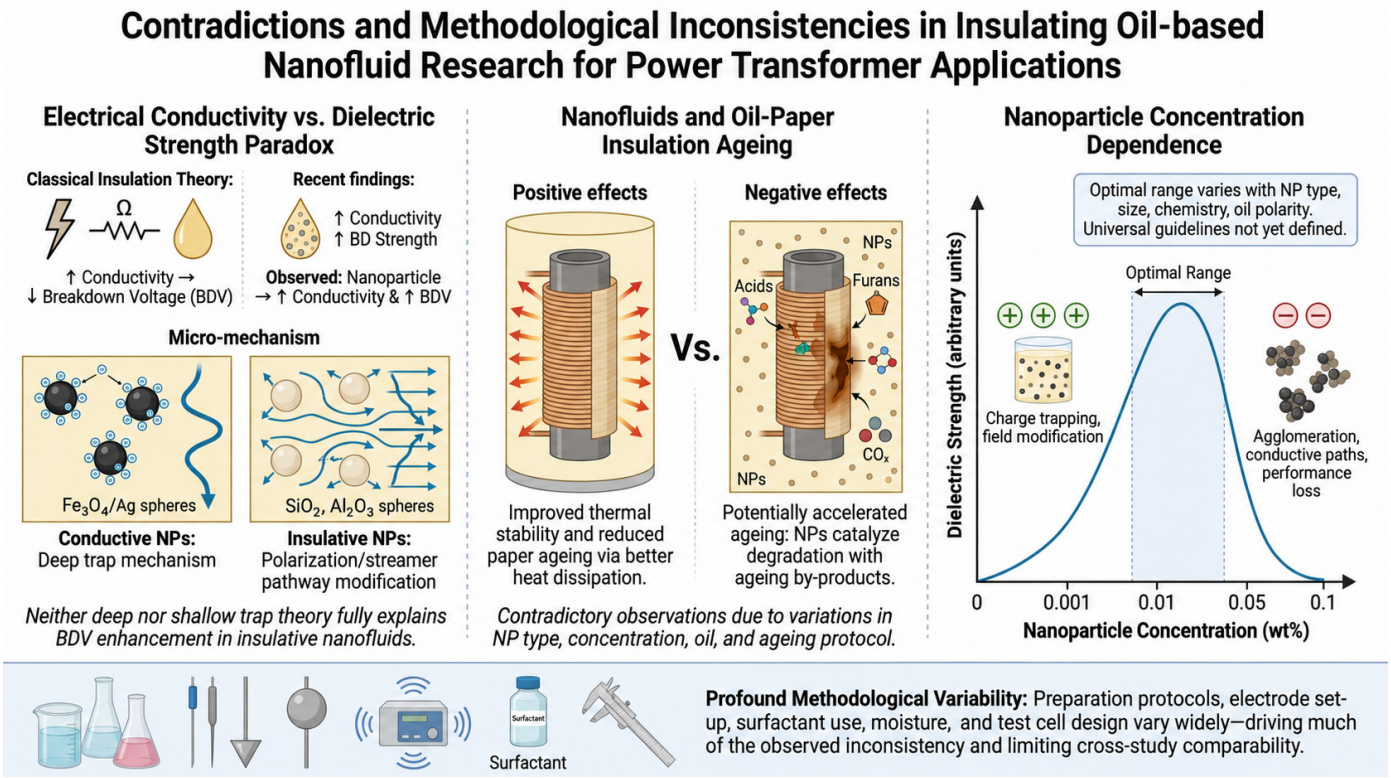


Figure 7. Contradictions and methodological inconsistencies in insulating oil-based nanofluids.

7. Limitations in Industrial Viability and Prospects

Despite the compelling body of experimental evidence demonstrating the potential of insulating oil-based nanofluids to simultaneously enhance the dielectric, electrical, and thermal performance of transformer insulation systems, their transition from laboratory demonstration to industrial deployment remains a formidable challenge. Power transformers are engineered to operate reliably for 32–55 years under continuously varying electrical, thermal, and environmental conditions, a service-life expectation that imposes stringent, non-negotiable requirements on any candidate insulating-fluid modification [155,199]. Within this demanding operational context, the integration of nanoparticles into liquid insulation systems raises a series of interconnected scientific, technological, economic, and regulatory challenges that must be systematically addressed before insulating nanofluids can be considered genuinely viable for industrial transformer applications [41,200]. The following subsections critically examine these challenges, identify the key methodological limitations of the current literature, and outline the most pressing research gaps and future directions for the field.

7.1. Long-Term Colloidal Stability Under Operational Conditions

The long-term colloidal stability of nanoparticles dispersed in insulating fluids represents arguably the most fundamental barrier to industrial deployment. As established in Section 3, nanoparticles are inherently susceptible to agglomeration and sedimentation driven by van der Waals attractive forces, electrostatic interactions, and gravitational settling, processes that progressively alter the effective nanoparticle concentration and degrade both dielectric and thermal performance over time [77,201]. In operational transformers, this challenge is substantially compounded by service conditions that are far more demanding than those typically reproduced in laboratory studies. Thermal cycling,

with transformer oil temperatures routinely fluctuating between ambient conditions and peak operating temperatures exceeding 90–110 °C, modifies interparticle forces and promotes thermally driven particle aggregation and migration [202]. High electric fields applied continuously during transformer operation can induce electrophoretic migration of nanoparticles toward electrode regions, creating non-uniform concentration gradients that locally alter dielectric properties. The oil circulation in actively cooled transformers introduces hydrodynamic shear forces that may either assist dispersion or, at high flow rates, promote particle-wall interactions and localized sedimentation [202]. Critically, the zeta potential of nanoparticle dispersions, the primary quantitative indicator of colloidal stability, with values exceeding ±30 mV considered stable, has been shown to decrease progressively with thermal aging, indicating that nanofluids that appear stable under ambient laboratory conditions may lose colloidal integrity under realistic transformer operating temperatures [77,201]. Addressing this challenge requires developing thermally robust surface functionalization strategies and conducting systematic long-term stability studies under conditions representative of real transformer operation.

7.2. Nanoparticle Migration, Sedimentation, and Material Compatibility

Beyond bulk colloidal stability, the spatial redistribution of nanoparticles within the transformer tank represents a distinct and practically significant concern. Under the combined influence of gravity, thermal convection gradients, and applied electric fields, nanoparticles may migrate preferentially toward specific regions of the transformer, accumulating at the bottom of the tank, concentrating near high-field electrode regions, or depositing onto solid insulation surfaces [203]. Such non-uniform distribution creates local variations in dielectric properties that may introduce new regions of electrical stress concentration, potentially compromising insulation integrity in ways that are difficult to predict or monitor [204]. Sedimented nanoparticles accumulating at metallic surfaces raise additional concerns regarding electrochemical interactions between nanoparticles and transformer structural materials, including copper windings, steel cores, and aluminum components, which could catalyze oil oxidation, generate metallic contaminants, or alter the chemical composition of the insulating fluid over time. Furthermore, the compatibility of nanofluids with transformer sealing materials, including nitrile rubber, silicone, and fluoropolymer gaskets, and with cellulosic solid insulation (kraft paper, pressboard) has not been comprehensively evaluated in the literature, representing a critical knowledge gap that must be addressed before industrial deployment can be responsibly pursued [205].

7.3. Compatibility with Ageing Products and Oil-Paper Insulation Systems

In operational transformers, the insulating fluid does not function in isolation; it exists in close contact with cellulosic solid insulation (kraft paper and pressboard) whose thermal and hydrolytic degradation continuously generates a complex mixture of ageing by-products, including organic acids, furanic compounds (2-furfural,5-hydroxymethyl-2-furfural), carbon oxide (CO, CO_2), and other chemical species [43,206]. The presence of nanoparticles in the insulating fluid introduces the possibility of physicochemical interactions between nanoparticle surfaces and these ageing products, interactions that could manifest as nanoparticle surface adsorption of organic acids (potentially modifying surface charge and colloidal stability), catalytic acceleration or inhibition of cellulose degradation reactions, or chemical modification of the fluid's oxidation stability [207]. These interactions have potentially significant implications for transformer diagnostic methodologies: dissolved gas analysis (DGA), furanic compound analysis, and dielectric response techniques, the primary tools used for transformer condition monitoring, rely on well-established correlations between measured chemical or electrical indicators and the state of insulation

degradation [208]. If nanoparticles systematically alter the production rates or distribution of these diagnostic markers, the reliability of conventional diagnostic interpretations in nano-modified transformers could be compromised, a concern that has received remarkably little attention in the current literature and demands urgent systematic investigation [209].

7.4. Industrial Deployment: Technological, Economic, and Regulatory Barriers

The path to industrial deployment of insulating nanofluids faces substantial technological, economic, and regulatory barriers that extend well beyond the scientific challenges discussed above. At the manufacturing level, producing nanofluids at an industrial scale with consistently uniform nanoparticle dispersion, reproducible particle size distribution, and guaranteed long-term stability requires sophisticated manufacturing infrastructure, including large-scale ultrasonication systems, controlled-atmosphere processing environments, and rigorous quality control protocols, which significantly increases production complexity and cost relative to conventional insulating oils [210]. From an economic perspective, the higher procurement cost of engineered nanoparticles, combined with increased manufacturing complexity, means that insulating nanofluids currently carry a substantial cost premium over conventional mineral oil and ester-based fluids, a premium that must be justified by demonstrable long-term performance and reliability benefits before power utilities and transformer manufacturers will consider adoption at scale [210]. At the regulatory level, current international standards for transformer insulating fluids, including IEC 60296:2020 [211] (mineral oil), IEC 62770:2024 [212] (natural esters), and IEC 61099:2010 [213] (synthetic esters), do not yet include provisions specifically addressing the characterization, performance evaluation, or qualification requirements for insulating nanofluids. This regulatory gap represents a significant institutional barrier, as transformer manufacturers and power utilities are generally unwilling to adopt non-standardized insulating fluids without clear regulatory guidance and liability frameworks [205]. Thus, detailed quantitative economic assessment and a regulatory framework for the commercialization of dielectric nanofluids remain paramount bottlenecks. The green synthesis of nanoparticles may reduce cost, energy consumption, and hazardous-reagent use compared to conventional nanoparticle synthesis [6,214,215]. However, these potential savings may be offset by the cost of purification, drying, ultrasonication, surfactant addition, quality control, and batch-standardization requirements. At present, there are insufficient data on production cost per liter, additional pumping energy consumption, maintenance frequency, fluid-replacement intervals, and payback period to help assess the actual cost of scalability [216]. Therefore, future research should include techno-economic analysis comparing nanoparticle and processing costs with possible benefits such as longer insulation life, fewer outages, and delayed transformer replacement. Maintenance, recycling, nanoparticle recovery, and final disposal costs should also be included. Such coordinated validations are indispensable for researchers, standard organizations, transformer manufacturers and utilities before the commercialization of dielectric nanofluids.

7.5. Methodological Limitations and Research Gaps

A critical examination of the existing literature reveals several systematic methodological limitations that currently prevent reliable quantitative comparison between studies and limit the translational value of reported findings for industrial applications [217,218]. The most pervasive limitation is the absence of standardized experimental protocols for nanofluid preparation, characterization, and dielectric testing, with significant inter-study variability in nanoparticle dispersion techniques, electrode geometries, electrode gap, voltage waveforms, thermal conditioning procedures, and moisture control practices [219,220]. This variability makes direct cross-study comparison of reported BDV, PDIV, and thermal

conductivity enhancements highly problematic and may partly explain the considerable spread in reported performance data across the literature. Moisture control is a particularly critical yet frequently overlooked variable: given that moisture content strongly influences both dielectric breakdown strength and cellulose ageing kinetics, the failure of many studies to precisely document and control moisture levels in both the insulating fluid and solid insulation introduces substantial uncertainty into reported results [221]. The quality and characterization of nanoparticle dispersion are similarly inconsistent across studies, with many investigations relying solely on ultrasonication without providing particle size distribution data, zeta potential measurements, or long-term stability assessments, making it impossible to determine whether reported performance variations reflect genuine nanoparticle effects or simply differences in dispersion quality [73,222]. Most critically, the overwhelming majority of experimental studies evaluate nanofluid properties in isolation from solid insulation, ignoring the coupled oil-paper-moisture interactions that govern the behavior of real transformer insulation [223,224]. Combined with the short duration of most ageing experiments (typically a few hundred to a few thousand hours, compared to transformer service lives exceeding several decades), these limitations mean that the long-term impact of nanoparticles on transformer insulation reliability remains fundamentally unresolved [225,226].

7.6. Future Research Directions and Roadmap

Addressing the challenges and gaps identified above requires a coordinated and multidisciplinary research agenda spanning materials science, electrical engineering, chemical engineering, and transformer systems engineering.

The most critical priorities include: (1) development of a unified theoretical framework integrating charge trapping, streamer propagation, and interfacial polarization mechanisms to consistently describe nanofluid dielectric behavior under realistic transformer electrical stress conditions [227,228]; (2) systematic long-term ageing studies of nano-modified oil-paper insulation systems under accelerated but representative transformer operating conditions, providing statistically robust data on nanofluid stability and its impact on insulation lifetime [86]; (3) comprehensive investigation of nanofluid-diagnostic indicator interactions to assess whether conventional DGA, furanic compound, and dielectric response methodologies remain valid in nano-modified transformers [208,209]; (4) development and international adoption of standardized testing protocols for insulating nanofluids within the IEC and ASTM standardization frameworks [205]; (5) development of multiphysics modelling frameworks coupling electrical, thermal, chemical, and ageing processes to enable holistic simulation of nanofluid as transformer insulation medium, a capability that would dramatically accelerate the rational design and optimization of insulating nanofluids for specific transformer applications [229,230]; (6) unwanted spillage of non-biodegradable insulating oils and also the use of toxic nano-additives in insulating oil-based nanofluids are important environmental hazards. While Ester-based biodegradable insulating oils overcome the environmental risks of non-biodegradable mineral oil, the addition of nanomaterials to insulating oil-based nanofluids has received insufficient attention. The environmental fate of nanoparticles following nanofluid spillage, including their mobility in soil and groundwater, bioaccumulation potential, ecotoxicological effects and long-term persistence, has not been systematically studied for any insulating nanofluid formulation.

Progress across these research fronts will be essential for transforming insulating oil-based nanofluids from a promising laboratory technology into a reliable, standardized, and commercially viable solution for next-generation power transformer insulation systems.

The plausible limitations in industrial viability and prospects of dielectric nanofluids are graphically illustrated in Figure 8.

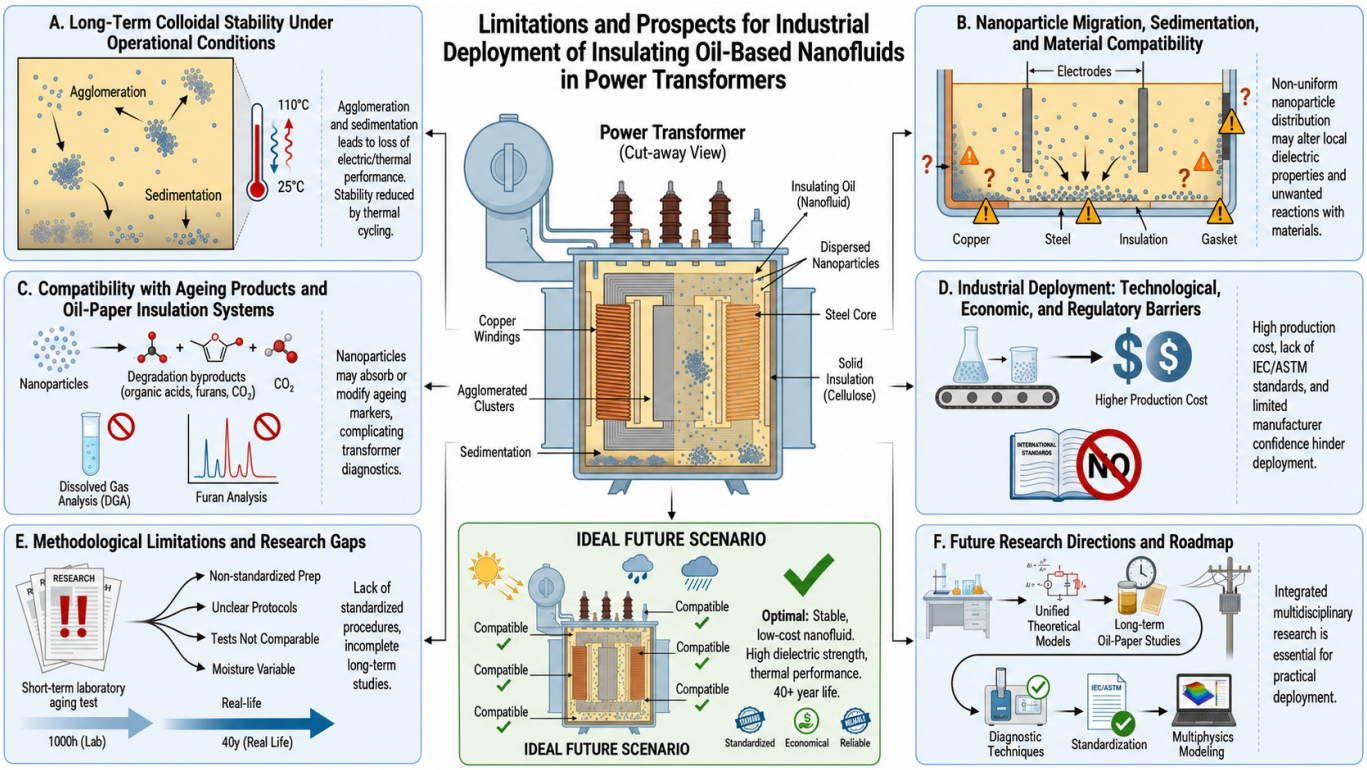


Figure 8. Limitations in industrial viability and prospects of Nanofluids.

8. Conclusions

This review has presented a comprehensive and critically structured analysis of insulating oil-based nanofluids for power transformer applications, spanning their historical foundations, synthesis and stabilization methodologies, characterization techniques, dielectric and thermal performance, and the multidimensional challenges that currently impede their industrial deployment. The following principal conclusions can be drawn from the synthesized body of evidence. The historical development of insulating oil-based nanofluids, from the foundational nanofluid concept introduced by Choi and Eastman (1995) [49] and the first electrical insulation application by Segal et al. (1998) [50] followed by the theoretical frameworks of trap theory (2010) [54] and shallow trap theory (2012) [55], to the recent emergence of hybrid and carbon-based nanofluid systems, demonstrates a field that has matured rapidly and continuously to expand in both scientific depth and technological ambition. The mechanistic understanding of dielectric enhancement, rooted in nanoparticle-mediated electron trapping, streamer suppression, and local electric field modification, now provides a reasonably well-established theoretical foundation and experimental evidence, though a unified predictive framework that describes nanofluid behavior across all nanoparticle types, base oils, and operating conditions remains an important unresolved challenge.

From a synthesis and stabilization perspective, the two-step preparation method, combining independent nanoparticle synthesis with controlled dispersion through ultrasonication, surface functionalization, and surfactant-assisted stabilization, has emerged as the most practically viable route for producing dielectric nanofluids with acceptable colloidal stability. Probe ultrasonication, optimized surface functionalization using agents such as oleic acid and CTAB, and rigorous zeta potential monitoring (targeting magni-

tudes exceeding ±30 mV) are collectively essential for achieving the dispersion quality required for reproducible and reliable performance. Nevertheless, the optimal preparation parameters, including sonication power, duration, and surfactant concentration, remain system-specific and have not yet been generalized across nanoparticle-oil combinations.

In terms of dielectric and electrical performance, the experimental literature consistently demonstrates that optimally formulated insulating nanofluids outperform their base oils across multiple critical metrics. AC breakdown voltage enhancements of 20–60%, lightning impulse breakdown voltage improvements of up to 10–40%, partial discharge inception voltage increases of 15–40%, and dielectric loss reductions of up to 97% have been reported for various nanoparticle-oil systems at optimized concentrations. Metal oxide nanoparticles, particularly TiO_2, Al_2O_3, ZnO, and Fe_3O_4, and carbon-based nanomaterials, including graphene oxide, carbon nanotubes, and fullerene C_{60}, represent the most extensively studied and promising categories of nano-additives, each offering distinct and complementary performance advantages. Critically, all performance enhancements exhibit a non-monotonic concentration dependence, with optimal performance achieved within narrow concentration windows and deterioration occurring at higher loadings due to agglomeration and percolation effects. With respect to the thermal performance, while nanoparticle incorporation can enhance thermal conductivity by 10–40%, with carbon-based nanomaterials offering the most significant improvements, this enhancement is invariably accompanied by increased dynamic viscosity, creating a fundamental thermo-viscous trade-off that must be carefully managed through system-level optimization to ensure net improvements in transformer cooling efficiency.

Despite these promising advances, the path to industrial deployment remains obstructed by a series of interconnected challenges: long-term colloidal instability under realistic transformer operating conditions, nanoparticle migration and sedimentation within the transformer tank, uncertain compatibility with cellulosic insulation ageing products, potential interference with established transformer diagnostic methodologies, and the complete absence of internationally standardized testing and qualification protocols for insulating nanofluids within existing IEC and ASTM frameworks. Looking forward, the realization of insulating nanofluids as a commercially viable transformer insulation technology will require coordinated progress across several research frontiers: the development of thermally robust stabilization strategies, comprehensive long-term oil-paper ageing studies under representative operational conditions, systematic investigation of nanofluid-diagnostic indicator interactions, establishment of international standardization frameworks, and the development of multiphysics modelling tools capable of holistically describing the coupled electrical, thermal, chemical, and ageing behavior of nano-modified insulation systems. The insights in this review are intended to serve as a rigorous scientific foundation and strategic guide for researchers, engineers, and standardization bodies working toward the next generation of safer, more reliable, environmentally sustainable, and commercially viable power transformer insulation systems.

Author Contributions: M.F.: Conceptualization, methodology, validation, formal analysis, investigation, writing—original draft preparation, writing, review and editing, S.J.: writing, review, editing, and validation, A.B.Y.: editing, validation, Q.C.: figures and editing, C.T.: supervision, validation, writing, review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: The authors declare that this research received no external funding, and no APC was incurred for this review article.

Data Availability Statement: The data underlying this manuscript are presented within this review article. However, additional details can be shared upon reasonable request.

Acknowledgments: The figures in this manuscript were prepared with the assistance of FigureLabs V4.1, an AI-powered scientific illustration tool. All figures were critically reviewed, verified for scientific accuracy, and approved by the authors, who take full responsibility for the content presented.

Conflicts of Interest: The authors declare no conflicts of interest.

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