IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received September 8, 2019, accepted September 30, 2019, date of publication October 11, 2019, date of current version October 30, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2946633

Recent Progress and Challenges in Transformer Oil Nanofluid Development: A Review on Thermal and Electrical Properties

DANIAL AMIN[1], RASHMI WALVEKAR[1], MOHAMMAD KHALID[2], MAHESH VAKA[1],
NABISAB MUJAWAR MUBARAK[3], AND T. C. S. M. GUPTA[4]

[1]Sustainable Energy and Green Technology Research Group, Faculty of Innovation and Technology, School of Engineering, Taylor's University, Subang Jaya 47500, Malaysia
[2]Graphene and Advanced 2D Materials Research Group (GAMRG), Sunway University, Subang Jaya 47500, Malaysia
[3]Department of Chemical Engineering, Faculty of Engineering and Science, Curtin University Malaysia, Sarawak 98009, Malaysia
[4]Apar Industries Limited, Chembur, Mumbai 400071, India

Corresponding author: Rashmi Walvekar (rashmi.walvekar@gmail.com)

This work was supported by Taylor's University through the Taylor's Research Scholarship Programme.

ABSTRACT Transformer oil is refined electrical insulating oil, which is extremely stable at high temperatures and possesses excellent electrical insulating properties. These special types of oils are widely used in high voltage apparatus such as power transformers, high voltage capacitors and circuit breakers. Traditionally, mineral oils have been most commonly used as a coolant or as electrical insulation medium. However, the main concern related to mineral oil is overheating, overloading, short circuits that reduce the shelf life of the transformer unit and restrict its function as a reliable coolant. Moreover, other factors such as high electrical insulation requirements, safety and economic aspects need to be considered for the development of new insulating liquid material. Nanofluids have become the one of the alternatives for the existing products available in the market because of its high thermo-physical and good dielectric properties. This review focuses on the status of nanofluids, the effect of different nanoparticles to enhance the dielectric as well as its heat transfer properties of nanofluids. The thermo-physical properties of the newly developed transformer oil based nanofluids reported in comparison with different oils. Finally, future directions and challenges need to be addressed.

INDEX TERMS Transformer oil, nanofluids, dielectric strength, heat transfer, coolant.

I. INTRODUCTION

From the last few decades, transformer oils been effectively used as insulating and coolant materials due to their thermal and insulating characteristics. However, 75% of the transformers fail due to inappropriate dielectric insulation and extra power requirement. Transformer is one of the most essential electrical components as it serves a vital link in distributing electricity to the consumers [1]. It is known to be high-cost component and has a direct effect on network operation, location, oil contents and toxic material where any interruption on the transformer would reduce the reliability of the power system [2]–[4]. One of the suspects that cause transformer failure is overheating and thermal stress. Overheating and thermal stress holds about 32% of causes on transformer failures [5]. Intense researches and possible approaches must be developed to overcome all these failures. The potential solution to improve the insulation shell life and other properties are by the suspension of nanoparticles into the transformer oil, which enhances the thermal and dielectric insulating properties. Nanofluids are nano-sized particles dispersed into the base fluid that recently grabbed a lot of attention due to its unique and superior properties. However, researchers are still investigating the best possible combination of nanofluids with a desired characteristic, which remains unanswered. This review provides insight about the evolution, types of transformer oil, preparation of nanofluids and thermo-physical properties but also presents a detailed description of the design, operating conditions and failures. In addition, it also gives comprehensive details of current challenges, future work and conclusion.

The associate editor coordinating the review of this manuscript and approving it for publication was Navanietha Krishnaraj Krishnaraj Rathinam.

A. TRANSFORMER INSULATING OIL – HISTORICAL BACKGROUND

During the 1870s and 1990s, petroleum based oils have been used as dielectric liquids in transformer system [6]. They provided superior insulation, which served the purpose as dielectric liquids and excellent heat transfer medium to remove heat generated by electrical losses. However, the downside is that paraffinic-based oils, in general, have high pour points due to its high paraffin wax content, which is unacceptable for use in power-distributing equipment exposed to low temperatures. Furthermore, the sludge that is build-up due to oxidation is insoluble in such oils, increasing its viscosity. High-viscosity oils reduced heat transfer capabilities, which lead to overheating and reduced shelf life.

Naphthenic-based transformer oil was later introduced to combat the mentioned challenges. Although naphthenic-based oils are more vulnerable in oxidation compared to paraffinic-based, the oxidized products are soluble that, resulted in reduction in viscosity [7]. Naphthenic-based oils have a lower pour point, which will remain fluid at low temperature in the transformer system. However, the concern when utilizing naphthenic-based transformer oil is its flammability. Askarels – synthetic chlorinated aromatic hydrocarbons were used as insulating oils to enhance the fire resistance. The first transformer to utilized askarel was in 1932 and continued until the 1970s where it was determined that they were no longer environmentally acceptable [8].

Later, silicone fluids were introduced as an alternative to chlorine-based oils later as it has excellent electrical insulating, anti-oxidative properties, higher fire point, low flammable fluids and exceptional thermal stability due to the high Si-O bonding energy [6]. It was utilized for more than 20 years but the information was insufficient to evaluate its insulation and diagnosis when compared to data for transformer system that relies on mineral oil [9]. Another alternative was introduced that paired with silicone fluids which are high temperature hydrocarbons (HTH). They possess good electrical insulation but are flammable with high fire points [6].

Chlorofluorocarbon-based fluids were commercially utilized that demonstrated good electrical insulation and are non-flammable. However, its boiling point is low and tends to vaporize at operating temperatures. Tetrachloroethylene-based fluids are non-flammable which was commercially introduced in 1980 under the tradename WECOSOL [10]. The fluid has low viscosity and showcased excellent heat dissipation trait. It was used alone or mixed with transformer mineral oil to improve lubricating properties at a lower cost [11]. However, it has relatively lower electrical insulation properties compared to mineral oil and compromised safe operations. In 1978, isopropyl biphenyl hydrocarbon fluids, composed of propylated biphenyl isomers, were used for electric insulation. It has a good electrical insulating property and its flammability was reported to be relatively lower than the other commercialized fluids. The development of different transformer oils and evolution shown in **Fig.1**.

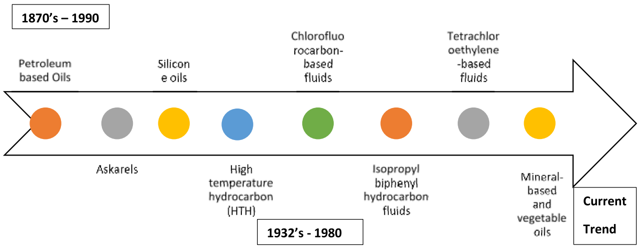


FIGURE 1. Timeline of different transformer oils and their development.

Different types of transformer oils in a different era is highlighted and their properties are also clearly mentioned in **Table 1**. Among all the different oils, silicone oil, high temperature hydrocarbons (HTH), chlorofluorocarbon-based fluids, and isopropyl-biphenyl hydrocarbon fluids show good electrical insulating properties. In addition, silicone oil also exhibits excellent thermal stability but still, the properties are not satisfactory.

B. TRANSFORMER – GENERAL DESIGN, OPERATING CONDITION AND CAUSES OF FAILURES

Transformers are normally found in industries that generate electricity, containing large numbers in various sizes from few kVA to over a few hundred MVA capacities [12]. Such vital electrical component is reliable in continuous operations that last 30 to 40 years of design life – some would go over 50 years [13]–[15]. In general, transformers contain few components – the main active component would be the winding and core that are responsible to alter voltages. Other components include load tap changer, bushing, insulation (oil and paper) and tank. Some heavy-duty transformers rely on oil to insulate high voltages and to dissipate heat. It consists of copper coils and a steel core linking them and is immersed in a transformer oil contained in the body tank.

According to Delta Transformers Inc, during the transformer operating, the maximum temperature rise attained was 65 °C and combined with the maximum ambient temperature of 40 °C, the operating temperature can lead up to 220 °C [16]. Its enclosure surface and hotspot in the transformer system could rise to 105 °C and 180 °C, respectively, at full load. High temperatures could stress the transformer system, leading to failure in operations. **Fig 2** below displays statistics of transformer failure between 2009 and 2013 in India. Different categories were analyzed over a period and failures for each category was reported clearly. Moreover, out of all Insulation shows a maximum of 80 failures, tank and coolant shows a minimum number of failures 6 and 9. On the other hand, it was reported that bushing and other secondary causes such as cooling are both responsible for 20% for transformer failure, which can be viewed in **Fig 3**. The bushing is an insulating component used in the transformer to allow high voltages safely flow through the grounded barrier. Since high voltages pass through, this insulating component

TABLE 1. Types of transformer fluids used in respective years.

Years	Transformer Fluids	Remark
1870s – 1990s	Petroleum-based oils	➢ Paraffin-based oils were used ➢ Prone to oxidation and have a high pour point ➢ Naphthenic-based oils were used as an alternative ➢ Prone to oxidation but the oxidized products are soluble – viscosity reduced ➢ Lower pour point but more flammable compared to paraffin-based oils
1932 – 1980s	Askarels	➢ Synthetic chlorinated aromatic hydrocarbons ➢ Used to enhance fire resistance ➢ Stopped in the 1970s as it was determined that it was not environmentally acceptable
	Silicone oils	➢ Introduced as an alternative to chlorine-based oils ➢ Excellent electrical insulating, anti-oxidative properties, higher fire point, low flammable fluids and exceptional thermal stability. ➢ Insufficient information to evaluate its insulation and diagnosis in those early years
	High temperature hydrocarbons (HTH)	➢ Used as another alternative to chlorine-based oils ➢ Possess good electrical insulation but flammable with high fire points
	Chlorofluorocarbon-based fluids	➢ Demonstrated good electrical insulation and are non-flammable ➢ Downside is that its boiling point is low and tend to vaporize during operations
	Isopropyl biphenyl hydrocarbon fluids	➢ Introduced in 1978 ➢ Composed of propylated biphenyl isomers ➢ Good electrical-insulating property and its flammability was relatively lower than other commercialized fluids
	Tetrachloroethylene-based fluids	➢ Introduced in 1980 under the tradename WECOSOL ➢ Used alone or mixed with transformer mineral oil to improve lubricating properties ➢ Low viscosity and showcased excellent heat dissipation trait ➢ Relatively lower electrical insulation properties compared to mineral oil

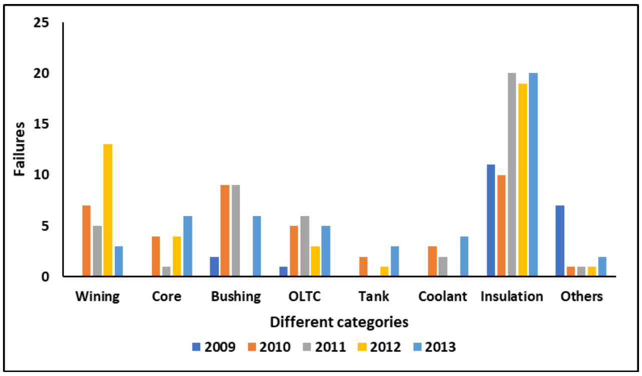


FIGURE 2. Statistics of transformer failure between 2009 and 2013 in India [18].

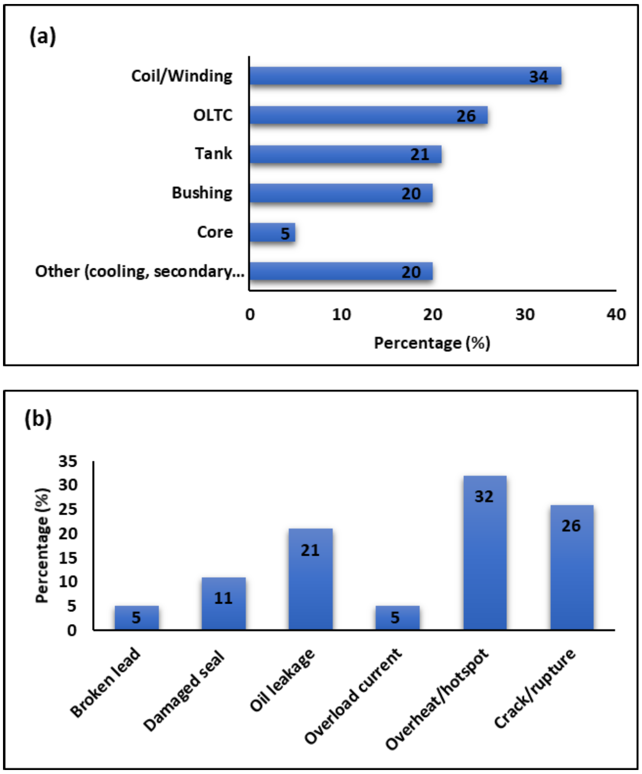


FIGURE 3. (a) Causes of transformer failure and (b) bushing failure [1].

deals with heat and requires transformer oil to cool it down. If the transformer oil could not dissipate heat, the bushing of the transformer will eventually fail. One of the reasons that led to bushing failure was overheating or hotspots, which covered the highest of 32%. According to e-Cigre [17], between 2004 and 2009, dielectric and thermal were noted as two of the root causes of transformer, which can be viewed in **Fig 4**.

Regardless of the type, transformer oils should possess reliable characteristics to ensure optimum and safe continuous operations. Two of the characteristics that should be heavily emphasized is its insulation and coolant. Transformer oil should have high dielectric strength to withstand high voltages generated by the transformer without breaking down. Besides, it should also possess high thermal conductivity for heat dissipation – relieve or cool down the system. **Table 2** below summarizes characteristics of reliable transformer oil should have.

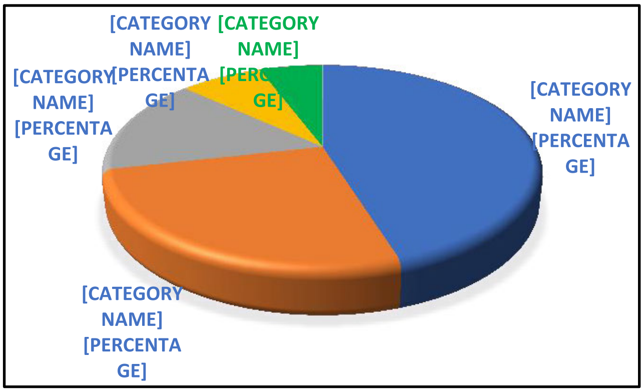


FIGURE 4. Classified failures according to failures modes from Cigre.

TABLE 2. Characteristics of reliable transformer oil [8].

Characteristics	Remarks
High dielectric strength	To withstand high voltages generated by transformers without breaking down or degrading the oil itself.
High thermal conductivity	To relieve or cool down the transformer system, countering the overheating challenge
Low viscosity	Ability to circulate and transfer heat will not be impaired
Resistance to oxidation	Ensure long life service and preventing the formation of sludge or other by-products due to oxidation
Free from acid and alkali	No presence of acid, alkali and corrosive Sulphur which could cause corrosion of metal parts in the transformer system and accelerate the sludge formation
Low pour point	Ensures the oil flows smoothly even at low temperatures for ease of circulation
High flash/fire point and low flammability	To ensure safer operation and reduce the risk of fatal accidents.
Environmental acceptable and low cost	Ensure the use of oil does not bring negative impact to the environment and economically viable.

II. TYPES OF TRANSFORMER OIL: MINERAL, VEGETABLE OR BLEND OIL

Over the years, different types of transformer oil have been studied to overcome the current challenges faced by power transmission systems. Apart from mineral oil, vegetable oils have been also investigated in detail. Vegetable oils are originated from plants and they usually referred to as plant oil. Vegetable oils are renewable, cheap, environmentally friendly, biodegradable and safer alternative insulating oil. Unlike mineral oil, they don't generate a poisonous substance from oxidative instability [19]. Many researchers investigated vegetable oils as a potential substitute for mineral oils while other researchers investigated mixtures or blend oils.

Till date, mineral oil is still extensively used as transformer oil as it is stable at high temperatures and easy to acquire since it is derived from crude oil. Silicone oils and synthetic esters were utilized as transformer oil but stopped as it deprived in safe operation and usage [6]. **Table 3** summarizes the comparison between mineral oil, silicone oil, synthetic ester and vegetable oil. Insulation and coolant are two of the crucial traits of transformer oil to ensure reliable transformer operations. Thermal conductivity is one of the key properties to evaluate heat dissipation of transformer oil that makes the product even better. Higher thermal conductivity ensures more heat to be transferred. Comparing the four types of transformer oil in table 3, vegetable oil, in general, has the highest thermal conductivity, ranging from 0.16 to 0.17 W/m.K. Dielectric constant and breakdown voltage are two of the properties to evaluate insulation of the transformer oil. Based on table 3, it can be seen vegetable oil has higher breakdown voltage and dielectric constant, ranging from 82 to 97 kV and 3.1, respectively. In other words, vegetable oils can resist

TABLE 3. Insulating properties of various types of transformer oil [19], [20].

Properties		Mineral Oils	Silicone Oils	Synthetic Esters	Vegetable Oils	Test Methods
Dielectric Breakdown, kV		30-35	36-60	45-70	82-97	IEC 60156
Relative Permittivity at 25 °C		2.1-2.5	2.6-2.9	3.0-3.5	3.1-3.3	IEC 60247
Viscosity	at 0 °C, cSt	<76	81-92	26-50	77-143	ISO 3104
	at 40 °C, cSt	3 to 16	35-40	14-29	16-37	
	at 100 °C, cSt	2-2.5	15-17	4-6	4-8	
Pour Point, °C		-30 - -60	-50 - -60	-40 - -50	-19 - -33	ISO 3016
Flash Point, °C		100 - 170	300-310	250-270	315-328	ISO 2592 (1)
Fire Point, °C		110 - 185	340-350	300-310	350-360	
Density at 20 °C, kg/dm^3		0.83 - 0.89	0.96-1.10	0.90-1.00	0.87-0.92	ISO 3675
Specific heat, J/g. K		1.6 - 2.0	1.5	1.8-2.3	1.5-2.1	ASTM E1269
Thermal Conductivity, W/m. K		0.11 - 0.16	0.15	0.15	0.16-0.17	DCS
Expansion Coefficient, 10^{-4} K^{-1}		7 - 9	10	6.5-10	5.5-5.9	ASTM D1903
Interfacial Tension (IFT), dynes/cm		40 - 45	25	-	25	-
Moisture Content, ppm dry oil		10 - 25	50	-	50-100	-
Heat Capacity, cal/g.°C		0.488	0.363	-	0.5-0.57	-
Chemical Type		Hydrocarbon	Organosilicon	-	Ester	-
Dielectric Constant at 25 °C		2.2	2.71	-	3.1	-
Volume Resistivity at 25 °C, ohm.cm		10^{14} - 10^{15}	10^{14}	-	10^{14}	-
Breakdown Voltage, kV		60	-	-	74	ASTM D1816, 2 mm gap electrodes
Impulse Breakdown Voltage, kV		145-145	136	-	116	-
Dissipation Factor (%)	at 25 °C	0.05 max	-0.01	-	0.25-1.00	-
	at 100 °C	0.3 max		-		
Grassing Tendency		-10 - -20	-	-	-50	ASTM D2300
Biodegradability, %		30	Very Low	-	97-99	CEC-L-33 (21 days)

higher voltage before it breaks down and able to partially be conducted. However, the drawback of vegetable oil is that it has high moisture content and prone to oxidation. Mineral and silicone oils have low moisture content and have a higher resistance to oxidation. Comparing its shelf life, mineral and silicone oils can sustain longer than vegetable oils.

Villarroel *et al.* [22] studied moisture diffusion coefficients of transformer pressboard insulation and compared two vegetable oils Bio Electra^{TM} and Bio Temp^{TM} that were derived from sunflower seeds. The general equation for moisture diffusion coefficients was determined that covered a wide range of temperatures, moisture concentration and insulation thickness. The equations of Bio Electra^{TM} and Bio Temp^{TM} were found and expected to be similar since both natural esters derived from sunflower seeds. Achmad Susilo et al. [23] investigated partial discharge characteristics and dissolved gas analysis of two types of fatty acid alkyl esters – Pastell 2H-08 and palm fatty acid ester (PFAE) and compared with mineral oil. It was reported that partial discharge of Pastell 2H-08 increased above 15 kV$_{rms}$ than that of mineral oil due to higher dissipation factor. The dissolved gas analysis confirmed that Pastell 2H-08 generated a higher amount of hydrocarbon gases than mineral oil. Yanuar Z. Arief *et al.* [24] compared two vegetable oils – palm fatty acid ester (PFAE) and FR3 with mineral oil. It was reported that PFAE resulted in the highest breakdown voltage of 48.92 kV. PFAE and FR3 have lower dissipation factor than mineral oil. However, three oils resulted in the same trend where dissipation factor increased as ageing time increased. Lastly, PFAE and FR3 have higher capacitance than the one in mineral oil. High capacitance indicates good insulation where the tan δ is low since it is inversely proportional. Low value of capacitance indicates the insulating oil is approaching electrical conduction [24]. Additionally, AC conduction analysis was carried out on computational simulation to evaluate dielectric characteristics with different vegetable oils – coconut oil and sunflower oil. From the simulation, it was found that coconut oil has a relatively higher dielectric strength. However, the dielectric strengths of all oils decreased as the electrode gap increases. **Table 4** shows the comparison of properties with mineral oil and studied vegetable oils.

In recent studies, Toudja *et al.* [25] reported mixtures of natural ester olive oil and naphthenic mineral oil. The mixture ratios were covered from pure mineral oil to 50% mineral and 50% olive oil to pure olive oil. Hiramatsu *et al.* [26] studied the effect of water on breakdown properties of Envirotemp FR3, which is derived from soybean oil, and mineral oil mixtures. Mineral oil was mixed into Envirotemp FR3 with weight percentage ranging from 0 to 20. Yu *et al.* [27] studied the breakdown voltage of mineral oil and Envirotemp FR3 mixtures ranging from 0% mineral oil and 100% Envirotemp FR3 to 100% mineral oil and 0% Envirotemp FR3. **Table 5** summarizes the findings of the reported blend oil mixtures with its outcomes.

Li *et al.* [28] reported thermal ageing of 20 vol% rapeseed oil and 80 vol% mineral oil mixtures. Dielectric loss of the studied mixtures was found to be slightly lesser compared to one in pure mineral oil after 50 days of thermal aging. The breakdown voltage of the oils decreased with ageing time but mixture of 80 vol% mineral oil and 20 vol% rapeseed oil resulted higher compared to pure mineral oil when the ageing time was higher than 50 days. Johari *et al.* [29] compared breakdown voltage of palm fatty acid ester (PFAE) with soybean-based Envirotemp FR3 (FR3). Breakdown voltage of both biodegradable oils decreased with ageing period. However, PFAE resulted higher breakdown voltage than FR3

TABLE 4. Summary of recent research on vegetable oil as transformer oil.

Properties			**Villarroel et al.** [22]			**Achmad Susilo et al.** [23]		**Yanuar Z. Arief et al.** [24]	
			Bio Electra^{T}	Bio Temp^{TM}	Mineral Oil	PFAE	Palm Oil	Coconut Oil	Sunflower Oil
Electrical	Dielectric Strength, kV		65	65	70-75/2.5 mm	85	75	60	38-45
	Relative Permittivity		-	-	2.2 @ 80 °C	2.95 @ 80 °C	3.10 @ 40 °C	2.79 @ 20 °C	3.1 @ 25 °C
	Tan δ		-	-	0.001 @ 40 °C	0.31 @ 80 °C	0.03 @ 25 °C	0.08 @ 20 °C	0.0093 @ 25 °C
	Volume Resistivity		-	-	7.6 x 10^15	7.1 x 10^12	-	-	-
Physical	Viscosity	mm^2/s		-	8.13 @ 40 °C	5 @ 40 °C	300 @ 25 °C	29.8-31.6 @ 40 °C	43 @ 40 °C
		cSt	39.2 @ 40 °C	45.0 @ 40 °C			-	-	-
	Flash Point, °C		330	330	152	176	>220	225	<330
	Pour Point, °C		-26	-15	-45	-32.5	-	-	-
	Density	g/cm^3	-	-	0.88 @ 40 °C	0.86 @ 40 °C			
		Kg/m^3	-	-			0.9 @ 15 °C	0.917 @ 20 °C	0.919 @ 20 °C
Environmental	Total Acid value, mgKOH/g		-	-	0.04	<0.03	0.07	0.02	0.02
	Toxicity		-	-	<0.01	0.05	-	-	-
	Source		Sunflower Seeds	Sunflower Seeds	-	-	-	-	-

TABLE 5. Summary of results on blend oils.

Author	Mixture	Results
Toudja et al. [25]	Mineral Oil: 85% Olive Oil: 15%	Resulted in a significant drop in breakdown voltage by about 38% Increasing the olive oil proportions resulted in improved breakdown voltage with the highest improvement by about 31% (5% mineral oil and 95% olive oil)
Hiramatsu et al. [26]	Mineral Oil: 10-20 wt.% Soybean Oil: 80-90 wt.%	Degrades with more water content but resulted in consistency with 10-20 wt.% mineral oil. AC breakdown strength degrades with an increase in mixing ratio when no water content but elevates in 600 ppm water
Yu et al. [27]	Mineral Oil: 70% Envirotemp FR3: 30%	Breakdown voltage upgraded by 8.6%. Total acidity increased as the proportion of vegetable oil increases

by up to 7.14%. Viscosity of PFAE and FR3 increased after 200 hours of ageing period by up to 34.25% and 10.38%, respectively. Guerbas *et al.* [30] studied mineral oil and reclaimed used mineral oil, obtained from the Algerian transformer. Both oils resulted improved breakdown voltage after 315 hour of ageing period. However, the breakdown voltage of reclaimed oil decreased slightly until 531-hour ageing period while decreased drastically for the new mineral oil.

It can be seen vegetable oils have relatively higher breakdown voltage than mineral oil. Having a high breakdown voltage allows the transformer oil to resist higher voltages in the transformer system before it breaks and become semiconductive. However, two of the factors were studied that weaken the breakdown voltage of the transformer oil – water content and aging. Vegetable oils contain ester groups which could form hydrogen bonded water, depleting the breakdown voltage [27], [28]. Naturally, mineral oils do not contain ester groups and they have significantly lower water content, compared to vegetable oils. Aging, on the other hand, depletes breakdown voltage since the oils degrade over time. Both oils degrade due to oxidation forming oxidized products. Vegetable oils are prone to oxidation and degrade faster compared to mineral oil. Its oxidation products tend to be more acidic compared to mineral oils, which accelerates the aging rate [27]. Water content and acidity must be controlled to limit or slow down the aging and degradation processes to ensure longer shelf life. However, casting off vegetable oil should not be the option as it provides higher breakdown voltage than one in mineral oils. Vegetable oils contain triglycerides fats (saturated fat) which have orientation, atomic and electronic polarizations, resulting in higher breakdown voltage whereas mineral oil contains non-polar alkane chain molecules [33].

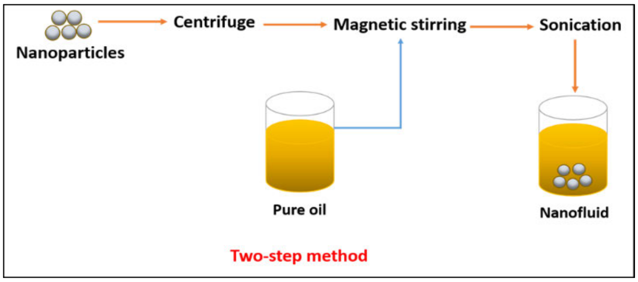


FIGURE 5. Preparation of nanofluids by a two-step method.

III. PREPARATION OF TRANSFORMER OIL NANOFLUID

Preparation of transformer oil based nanofluid primarily requires careful selection of nanoparticles with superior properties that helps to improve the thermal and dielectric properties of transformer oils. These nanoparticles are categorized into different groups based on their behavior and function such as conducting, semiconducting and insulating nanoparticles that are dispersed in transformer oil. The synthesis of nanofluids involves two methods 1) One-step method and 2) Two-step method.

In the one-step method, the making and dispersion of nanoparticles in a base fluid is simultaneously done through physical vapor condensation processes [34]. This method may not be cost effective and drying, transportation and nanoparticle dispersion are avoided that results in minimizing nanoparticle agglomeration. Furthermore, the uniform distribution of nanoparticles can be benefited when one-step method is utilized. The disadvantages for one-step method is the residual reactants that are left in the nanofluids due to incomplete reaction and stabilization [34]. The other disadvantage of using one-step method is determining the effect of nanoparticle without eliminating the impurities and large-scale production is very expensive. Furthermore, in one-step method, most of the nanofluids synthesized were metal-based nanoparticles such as copper, silver and tungsten [34].

On the other hand, two-step method initially involves preparing the dry-powdered nanoparticles by means of chemical or physical methods. Later, the powdered nanoparticles are dispersed into the base fluid with the aid of agitation such as ultrasonic or magnetic stirring (shown in **Fig 5**). Even though the process is longer, it is more economical to produce nanofluid, especially in large-scale applications.

Several researchers have reported that the use of different nanoparticles in base oils enhances the dielectric, heat transfer and insulation properties. For example, Fe_3O_4-transformer oil (mineral oil) nanofluids with nanoparticle concentration up to 0.02 vol% were synthesized by two-step method and have resulted in enhanced breakdown strength [35]. Another two-step method was utilized to synthesize TiO_2 nanofluids and resulted in improved breakdown

TABLE 6. **Methods used to synthesize transformer oil nanofluids.**

Author	Nanoparticle	Base Fluid	Loading	Synthesis Method
Choi et al. [37]	Al_2O_3 (13nm, rod-shapes of 2nm x 20-200 nm) AlN (50 nm)	Transformer Oil	Up to 4 vol %	Two-Step
Amiri et al. [40]	AGQD (5-17 nm, thickness <1nm)	Transformer Oil	0.001 wt.%	Two-Step
Ghasemi et al. [41]	Fe_3O_4 (23.2 nm diameter)	Transformer Oil	0.1 – 0.6 vol%	Two-Step
Rafiq et al. [42]	SiO_2 (dimensions not specified)	Transformer Oil	20 vol%	Two-Step
Bhunia et al. [43]	h-BN (~300-400 nm in length)	Transformer Oil	0.01 – 0.05 wt.%	Two-Step
Ilyas et al. [44]	Alumina (40 nm)	Mineral Oil	0.5 – 3 wt.%	Two-Step
Alicia et al. [38]	Graphene (12nm thickness, 4500 nm lateral size)	Transformer Oil	0.01 – 0.1 wt.%	Two-Step
Cavallini et al. [45]	Magnetite (10-50 nm) GO (20-50 nm) SiO_2 (5-20 nm)	Transformer Oil	0.1 – 0.5 g/l	Two-Step
Qing et al. [46]	SiO_2-GNP (12 nm)	Transformer Oil	0.01 – 0.08 wt.%	Two-Step
Aberoumand et al. [39]	WO_3 (60 nm diameter) Ag (dimensions not specified)	WO_3-Transformer Oil	1 – 4 wt.%	One-Step

strength with 0.00625 vol% nanoparticle concentration [36]. Choi *et al.* [37] synthesized Al_2O_3-transformer oil with nanoparticle loading of up to 4 vol%. Alicia *et al.* [38] synthesized graphene-transformer oil nanofluids with nanoparticle concentration ranging from 0.01 and 0.1 wt.%. However, Aberoumand and Jafarimoghaddam [39] utilized a one-step method to synthesize hybrid WO_3-Ag-transformer oil. Table 6 displays the various transformer oil nanofluids recently studied using one step and two-step methods.

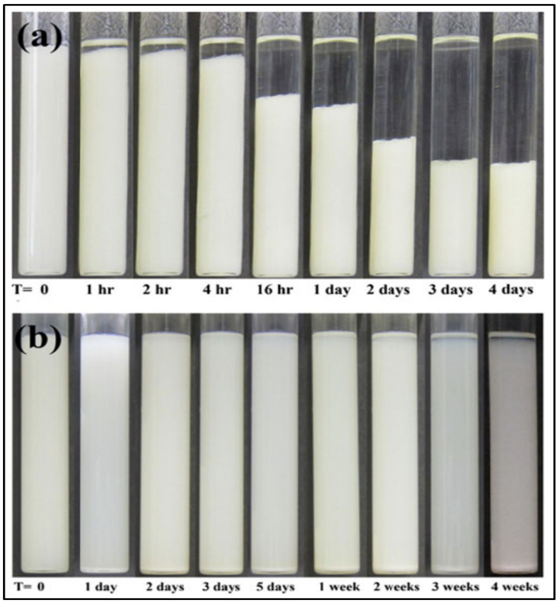


FIGURE 6. **Pictorial representation of different forces acting on nanoparticles that leads to sedimentation and aggregation when dispersed in transformer oil.**

A. STABILITY OF TRANSFORMER NANOFLUIDS

Stability is one of the key parameters that ensures the consistency of the functioning nanofluid and longer life cycle. Ensuring the long-life cycle of nanofluid possesses a challenge due to the agglomeration of nanoparticles. This aggregation is might be due to van der Waals forces of attraction or electrostatic repulsive forces lead to agglomeration of nanoparticles that limit the application shown in **Fig 6**. Researchers have developed many methods to analyze the stability of nanofluid such as Zeta potential analysis, light scattering, electron microscopy, spectral analysis and sedimentation method.

Ilyas *et al.* [44] utilized batch sedimentation apparatus using conventional visualization technique to analyze the stability of alumina-transformer oil nanofluid. The surface of alumina nanoparticles was modified by functionalizing carboxylic group using oleic acid and xylene. Results were observed that functionalized nanofluids do not show sedimentation over a month, which can be shown in **Fig 7**. However, slight sedimentation was observed at high concentration of 3 wt.% after 4 weeks. Taha-Tijerina *et al.* [47] observed high stability of h-BN-transformer oil after 3 months, with loading between 0.01-0.1 wt.% using zeta-potential method. Bhunia *et al.* [43] observed good stability oh h-BN-transformer oil nanofluid utilizing UV-vis spectroscopy. It was reported that stability dropped around 4% in the first 30 days and further dropped by 1% by the end of 3 months.

Alicia *et al.* [38] observed good stability with graphene-transformer oil nanofluid after 3 weeks utilizing UV-vis spectrophotometer as seen from **Fig 8**. Highest nanoparticle loading of 0.1 wt.% resulted in 5.1% of sedimentation at 170th hour before it stabilizes again.

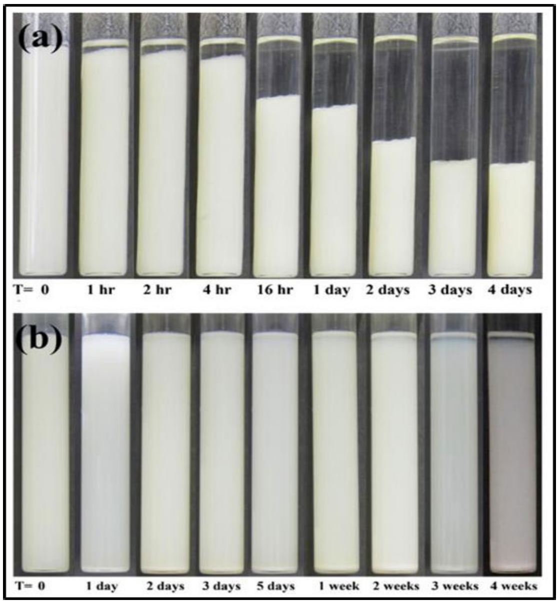


FIGURE 7. Sedimentation of alumina-transformer oil nanofluids at (a) natural and (b) functionalized conditions [44].

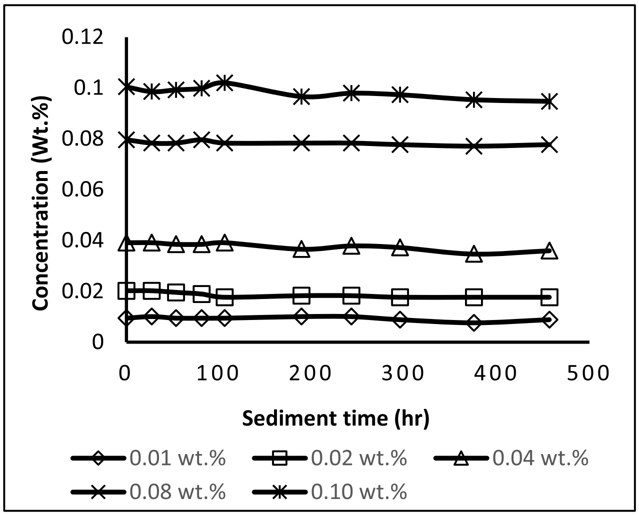


FIGURE 8. UV-vis Spectrophotometer of graphene-transformer oil nanofluid [38].

TABLE 7. Absolute zeta potential of Ag- WO_3-transformer oil nanofluid [39].

Nanoparticle Loading (wt%)	Absolute Zeta Potential (mV)	
	T = 40 °C	T = 100 °C
1	47	52
2	51	54
4	50	51

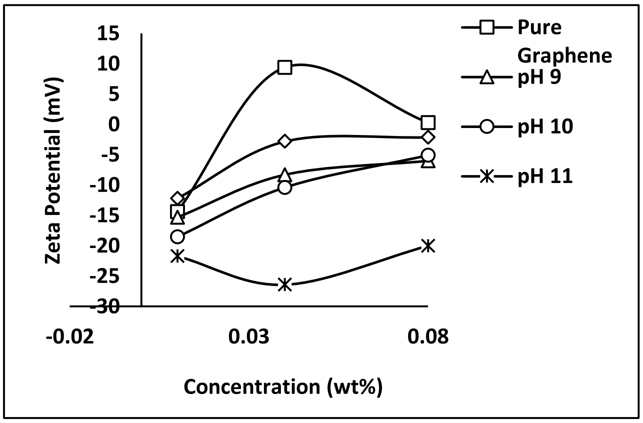


FIGURE 9. Zeta potential comparison SiO_2-graphene and pure graphene transformer oil nanofluid [46].

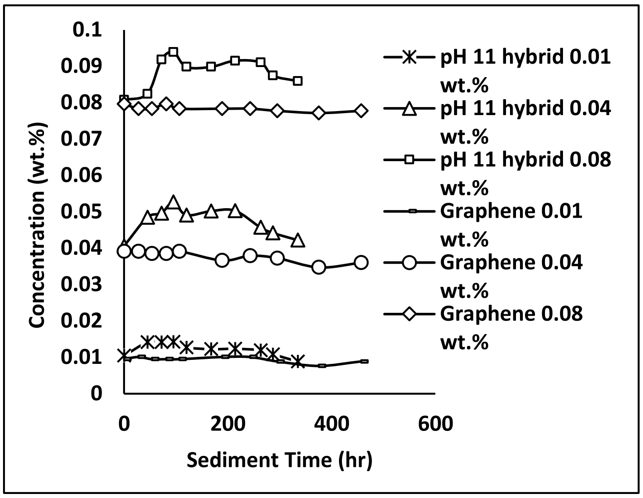


FIGURE 10. Stability comparison SiO_2-graphene and pure graphene transformer oil nanofluid synthesized at pH 11 [34], [42].

Aberoumand and Jafarimoghaddam [39] observed excellent stability after synthesizing hybrid Ag-WO_3-transformer oil nanofluid utilizing zeta potential measurement, as shown in **table 7**. Zeta potential increased from 1 wt.% to 2 wt% nanoparticle loading but decreased at 4 wt.% for both 40 °C and 100 °C. It was reported that measured nanofluid with zeta potential greater than 30mV is resulted to have high stability [48]. Qing *et al.* [46] synthesized hybrid SiO_2-graphene-transformer oil using sol-gel technique ranging from pH 9-12 whereby pH 11 depicted the highest colloidal stability measured using zeta potential, shown in **Fig 9**. It was reported that SiO_2 coating improves stability by increasing the repulsive electrostatic forces [49]. Amiri *et al.* [40] reported that stability of AGQD-based transformer oil nanofluid degrades by less than 0.5% after a month, confirmed by UV-Vis absorption spectra. **Fig 10** displays stability comparison between the use of graphene and hybrid SiO_2-graphene. It was reported that hybrid SiO_2-graphene with pH 11 has better stability than pure graphene. Higher stability will ensure the properties of nanoparticles are fully utilized in the transformer oil.

The above reported studies confirmed good stability and dispersion of nanoparticles in transformer oils. However, the study period was only varied between one week to one month. It should be noted that there is no mechanical stirring or agitation in the transformer system. Hence, nanoparticles have only natural convection to rely on good dispersion.

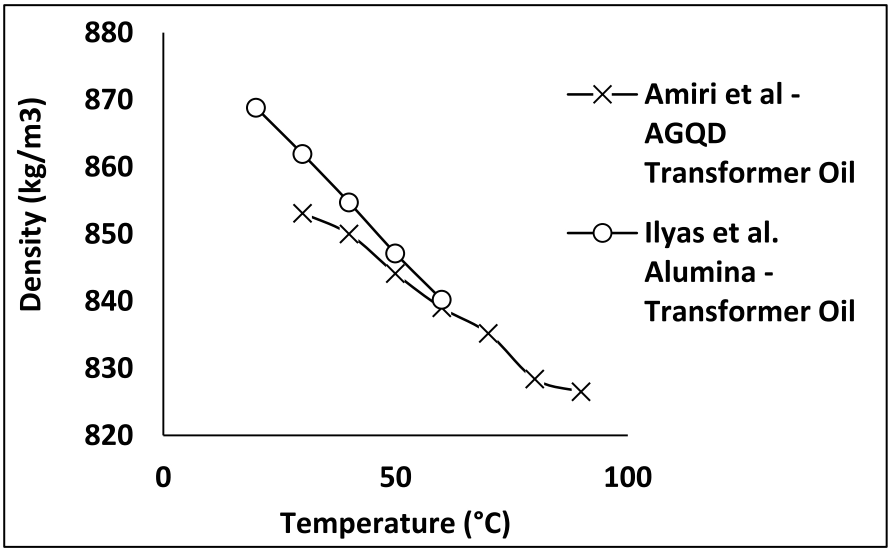


FIGURE 11. Density of alumina-transformer oil and AGCD-transformer oil nanofluid [36], [40].

Transformer oil should be able to withstand for long periods without sedimentation to ensure smooth and safe continuous operation. However, more studies need to be conducted to measure the stability of the nanofluids over a longer period and with varying operating temperatures.

The polarity of the nanoparticles influences nanofluid stability. Nanoparticles with high polarity tend to form clusters and eventually, agglomeration takes place [50]. Researchers have studied ways to overcome the agglomeration by modifying the surface of the nanoparticles to reduce the polarity behavior [36], [40], [42]. They reported that modifying the surface of the nanoparticles enhanced the repulsive electrostatic forces, improving the stability of the nanofluids. Besides, the addition of surfactants such as oleic acid reduces the agglomeration effect by weakening the bonds of nanoparticles [51].

IV. THERMO-PHYSICAL PROPERTIES

A. DENSITY

Density is one of the important parameters that vary with temperature. There is no mechanical mixing or agitation required inside the transformer system; hence, the fluid mixes via natural convection. Few studies have reported the density of oils as a function of nanoparticle concentration and temperature.

For instance, Ilyas *et al.* [44] predicted the density of functionalized alumina-transformer oil using a theoretical model proposed by Pak and Cho [52]. The results were found close to the experimental results for low nanoparticle concentrations. Density observed to increase with the addition of nanoparticles and decreased with temperature elevation. In another study, Amiri *et al.* [40] reported that the density of amine-based graphene quantum dots (AGQD)-transformer oil degrades as temperature elevates due to thermal expansion of oil. The maximum difference between pure transformer oil and AGCD-transformer oil was reported to be 0.23% at 40 °C, which is negligible.

Comparing Ilyas *et al.* [44] and Amiri *et al.* [40], it can be concluded AGQD-transformer oil depicted lower density compared to alumina-based transformer oil, which can be viewed on **Fig 11**. However, the difference is that the nanoparticle concentration used in AGQD-transformer oil is 0.001 wt.% whereas alumina-transformer oil used the highest in the study which is 3 wt.%. The deviation between these two transformer-oil nanofluids is not significant. Further studies are required to determine the effect of blend oils, nanoparticle size, type of nanoparticle and concentration of particles on the density of the nanofluid.

The concentration of nanoparticles and temperature affect the density of the nanofluid. Density increases with increasing nanoparticle concentration and decreases with rising temperature. The rise in temperature causes the liquid volume to expand causing its density to deplete. It should be noted that introducing nanoparticles to transformer oil enhances heat transfer properties. However, this advantage may be nullified due to the increase in density since it is dependent on buoyancy driven natural convection. Since agitator or stirring is absent in the transformer system, density, along with heat convection property, of transformer oil nanofluid should be studied as nanoparticles can only rely solely on buoyancy force for dispersion and stability.

B. VISCOSITY

The viscosity of the oil is a measure of resistance to the shear rate of the oil. It is also known as continuous flow circulation or resistance of the flow. The fluid that possesses low viscosity could lead to longer life cycle and more efficient equipment.

Ilyas *et al.* [44] reported decreased in dynamic viscosity of alumina-based transformer oil nanofluid with an increase in

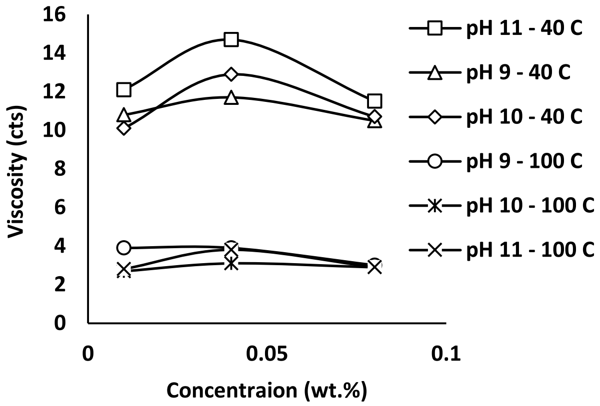


FIGURE 12. Viscosity of SiO_2-graphene nanofluids with respect to concentration and temperature [46].

temperature due to the weakening of intermolecular forces of attraction between molecules. They reported that the change of viscosity at different shear rates for temperature ranging from 20 °C to 90 °C is negligible. Besides, an increase in nanoparticle concentration resulted in a slight enhancement in dynamic viscosity but the effect was found to be insignificant at high shear rates. It was found that at 25 °C, high nanofluid concentrations enhanced dynamic viscosity by up to 18%.

Taha-Tijerina *et al.* [47] observed a drop in viscosit; from 16 mm^2 /s at room temperature to 2.2 mm^2 /s at 100 °C. The enhancement of viscosity was small with the addition of hexagonal boron nitride (h-BN) nanofillers. Besides, it was also reported that addition to the nanofillers up to 0.05 wt.% did not alter its viscosity but the effect was seen at higher nanoparticle loading of 0.35 wt.% (<30%).

Fontes *et al.* [53] observed a significant effect on the viscosity of MWCNT-based transformer oil nanofluid with a loading of 0.05 vol.%. At the same nanoparticle concentration, diamond-based nanofluid possessed lower viscosity compared to MWCNT-based oils. Similarly, Choi *et al.* [37] reported enhancement in transformer oil nanofluid viscosity with an increase in Al_2O_3 nanoparticle concentration up to 4 vol%.

Alicia *et al.* [38] reported a 24% enhancement in viscosity of graphene-based transformer oil. They observed that the viscosity decreases with the addition of graphene nanoparticle concentration due to its self-lubricating effect [54]. Similarly, Qing *et al.* [46] observed an increase in viscosity of hybrid SO_2i-graphene-based transformer oil with loading nanoparticle addition (from 0.01 to 0.04 wt.%) but decreased when further addition of nanoparticles due to self-lubricating properties. SiO_2 possesses the ability that can reduce friction in nanofluids [55]. They also reported that the highest viscosity reduction was 75% when temperature elevated from 40 °C to 100 °C and resulted in no clear trend between viscosity and pH. **Fig 12** displays the Viscosity of SO_2i-graphene nanofluids with respect to concentration and temperature.

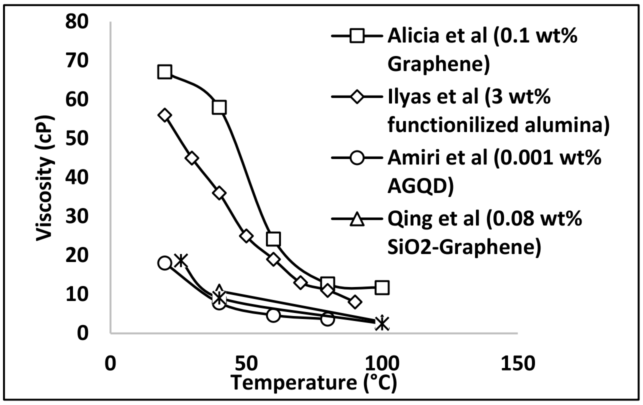


FIGURE 13. Viscosity comparison with different types of nanoparticles at highest studied concentration [34], [36], [40], [42], [43].

Amiri et al. [40] observed a sharp decrease in viscosity of amine-based graphene quantum dots (AGQD)-based transformer oil with an increase in temperature from 20 °C to 80 °C. Maximum enhancement of viscosity due to 0.001 wt.% nanoparticle loading was reported to be less than 1.3.

Some studies also reported a decrease in viscosity with temperature. This trait aids the dispersion and circulation of nanoparticles more freely in the transformer oil or base fluid. **Fig 13** below compiles the viscosity of different types of nanoparticles with the highest studied concentration. Taha-Tijerina *et al.* [47] showed low viscosity at 0.35 wt.% of h-BN nanoparticles, relatively close to Amiri *et al.* [40] with 0.001 wt.% AGQD nanoparticles. On the other hand, alumina-based transformer oil with 3 wt.% has better viscosity decrement compared with pure graphene at 0.1 wt.%. While **Fig 10** demonstrates the effect of pH and temperature on viscosity of SiO2/graphene based transformer oil [46]. The nanofluids clearly showed a decrease in viscosity at 100°C compared to 40°C. It was also observed that viscosity increased with pH at 40°C, which could be associated with the size of SiO_2 on graphene. However, at 100°C negligible effect of pH on viscosity was reported.

Like density, introducing nanoparticles to transformer oil would enhance its viscosity but decreases with rising temperature. The viscosity of the nanofluid increases with nanoparticle concentration due to the formation of clusters that were bonded by its forces of attraction, obstructing the flow of fluid [56]. It involves more energy to overcome the internal resistance of the nanofluid. However, the increasing temperature reduces the viscosity of nanofluid due to an increase in the average velocity of the Brownian motion of nanoparticles [57]. More energy is introduced to weaken the bonds of molecules, decreasing the internal resistance of the nanofluid. Low viscosity nanofluids are favorable since it allows fluid to flow easily and for nanoparticles to disperse.

C. THERMAL CONDUCTIVITY

Thermal conductivity is one of the key properties that has the capacity to conduct heat. The main motivation of transformer oils in upgrading the functionality and operability of

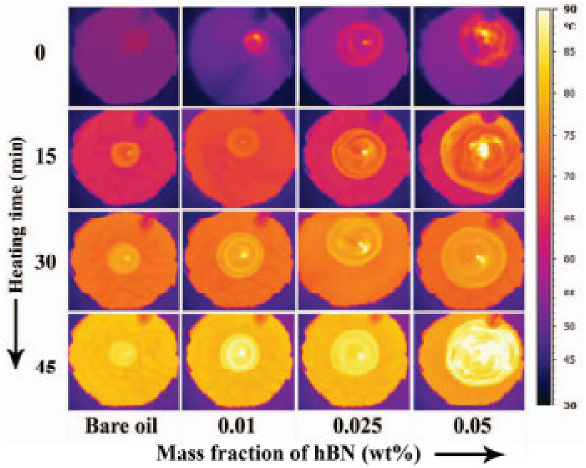


FIGURE 14. Thermal images of bare oil and nanofluid with heating time [43].

coolant or insulation is enhancing the thermal conductivity. This plays a vital role in increasing the heat transfer of the base fluid. Therefore, it is important for any desired fluid to have high thermal conductivity. This can be achieved by the addition of nanoparticles into the base fluids [58] Moreover, heavy-operating machines or equipment that generate heat requires coolant or cooling system. In brief, energy is transferred from one molecule to other due to high kinetic energy. The collision rate is enhanced with an increase in temperature due to Brownian motion. Thus, transformer oils or power transmission fluids are required to have high thermal conductivity to dissipate heat.

Ilyas *et al.* [44] reported that the thermal conductivity of functionalized alumina-based transformer oil enhanced with temperature elevation, from 25 °C to 55 °C, and nanoparticle concentration. They observed that the highest nanoparticle concentration of 3 wt.% resulted in the maximum thermal conductivity enhancement up to 16%. Taha-Tijerina *et al.* [47] observed enhanced thermal conductivity as temperature elevates, from 20 °C to 50 °C and addition of hexagonal boron nitride (h-BN) nanofillers. Enhancement of thermal conductivity was resulted to be by about 77% with h-BN loading of 0.1 wt.%. Fontes *et al.* [53] resulted in thermal conductivity enhancement in both diamond-based and MWCNT-based nanofluids. They observed that MWCNT-based nanofluid resulted in higher thermal conductivity ranging from 11 to 25% with varying nanoparticle concentration. However, the thermal conductivities were measured at a constant temperature of 20 °C.

Bhunia *et al.* [43] observed an enhancement in thermal conductivity with temperature and boron nitride nanosheets. Maximum thermal conductivity increment was about 45% with a loading of 0.05 wt.% nanosheets. Heating experiments were performed to demonstrate the temperature distribution profile, as shown in **Fig 14**. The temperature of the nanofluid quickly increased with particle concentration and heating time demonstrating the faster heat transport in the presence of nanoparticles.

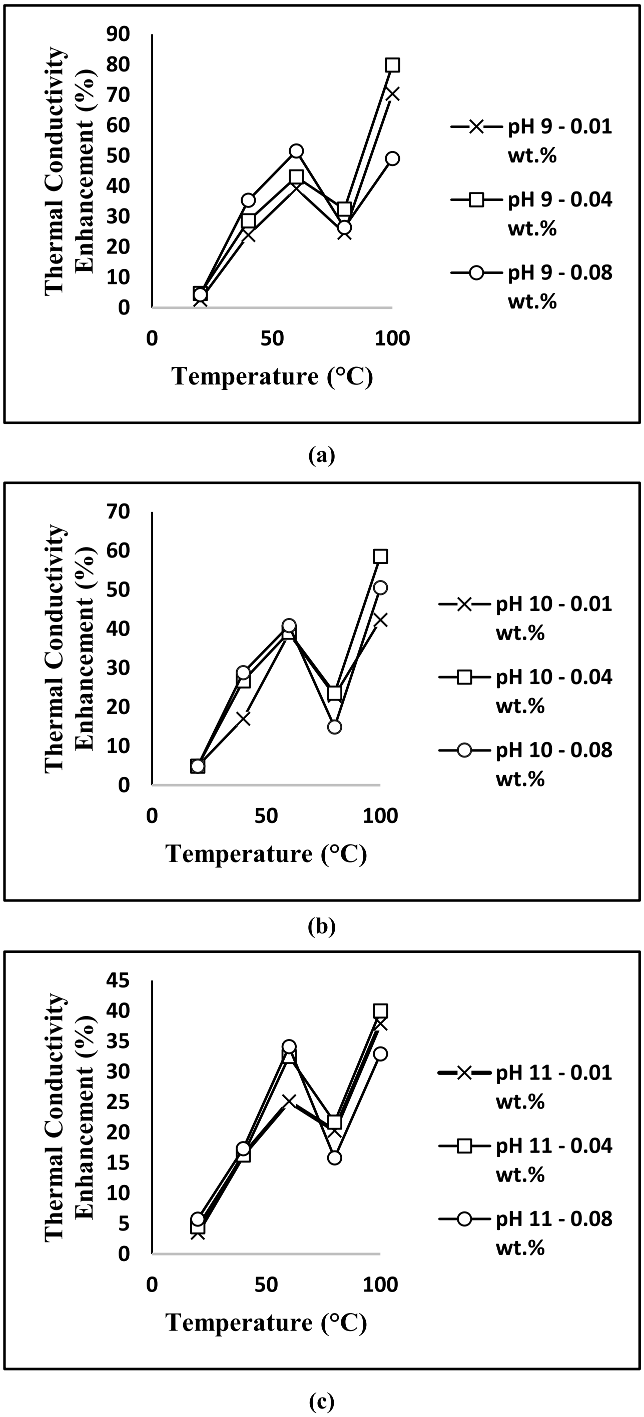


FIGURE 15. Thermal conductivity at (a) pH 9 (b) pH 10 and (c) pH11 hybrid SiO_2-Graphene transformer oil nanofluid [46].

Choi *et al.* [37] reported more than 20% enhancement at 4 vol% of Al_2O_3 nanoparticles. They also reported that AlN-based transformer oil has its thermal conductivity enhanced by 8% with 0.5 vol.% AlN nanoparticles.

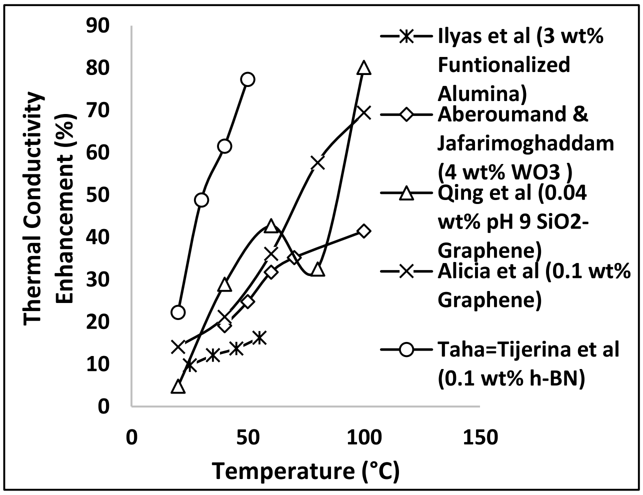


FIGURE 16. **Thermal conductivity enhancement comparison with respect to temperature [34], [35], [40], [42], [43].**

Alicia *et al.* [38] have reported maximum thermal conductivity of about 29% with respect to graphene concentration at 60 °C varying between 0.01 to 0.1 wt.%. On the contrary, with respect to temperature, 0.1 wt.% graphene loading showed thermal conductivity enhancement up to 69%. Drop in thermal conductivity at 40 °C was observed due to the nature of naphthenic transformer oil [59]. Aberoumand and Jafarimoghaddam [39] observed enhanced thermal conductivity as temperature elevates with Ag-WO_3-transformer oil nanofluids. Thermal conductivity was enhanced by 41% at 100 °C with WO_3 concentration of 4 wt.%.

Fig 16 below displays a comparison between thermal conductivity enhancements as a function of temperature. Transformer oil nanofluid synthesized by Qing *et al.* [46] observed the highest thermal conductivity increment with the addition of pH 9 and 0.04 wt.% silicon dioxide (SiO_2)-graphene nanoparticle concentration. However, the thermal conductivity of hexagonal boron nitride (h-BN) transformer oil nanofluid, prepared by Taha-Tijerina *et al.* [47], enhanced by 77% with maximum studied temperature of 50 °C and nanoparticle loading of 0.1 wt.%. Pure graphene-based nanofluid, synthesized by Alicia *et al.* [38], demonstrated thermal conductivity very close to Taha-Tijerina et al with the enhancement of 69% at 100 °C and nanoparticle concentration of 0.1 wt.%. Aberoumand and Jafarimoghaddam [39] observed thermal conductivity enhancement of 41% with 4 wt.% of tungsten (iii) dioxide (WO_3) at 100 °C. Researchers have observed an increase in thermal conductivity with rising temperature, regardless of the nanoparticle selection, due to the growing of Brownian motion. As temperature increases, the nanoparticles absorb more kinetic energy causing more particle collisions. Rate of particle collisions enhances with rising temperature due to Brownian motion. A higher concentration of nanoparticles would enhance thermal conductivity as more particle collision occur. However, nanoparticle concentration should be controlled as it would jeopardize other properties, especially stability and dielectric properties.

D. BREAKDOWN VOLTAGE & DIELECTRIC STRENGTH

Heavy-duty equipment or machines such as transformers deal high currents and voltages. Transformer oils not only need to dissipate heat but to withstand or insulate electric field to ensure safe operations. Having transformer oil with high dielectric strength or breakdown voltage at disposal will not only result in safe operations, but reduction of volume and mass of transformer itself could also be achieved. However, selecting the type of nanoparticles is crucial to ensure the breakdown voltage or dielectric strength does not deplete.

Aberoumand and Jarimoghaddam [39] observed degradation from 7.5% to 34% in the dielectric strength of hybrid transformer oil nanofluid as loading of nanoparticle increased. They reported that the introduction of silver nanoparticle dragged the dielectric strength. Amiri *et al.* [40] observed the enhancement of electrical conductivity with the introduction of AGQD. With nanoparticle loading of 0.01 wt.%, the electrical conductivity enhanced by less than 5%. They then tested the breakdown voltage of the nanofluid and resulted in a 2.2% enhancement compared to pure transformer oil.

Qing *et al.* [46] reported that hybrid nanofluids of pH 10 and 11 suppressed electrical conductivity by 97%. They found that electrical conductivity enhanced with the addition of nanoparticle concentration and degraded pH due to net charge effect of graphene particles. However, enhancing pH would increase SiO_2 concentration thus suppressing the electrical conductivity. Kopčanský *et al.* [35] observed better dielectric properties with less than 0.01 volume concentration of magnetic nanoparticles than pure transformer oil. They concluded that the field induced aggregation of magnetic particles affects the dielectric breakdown strength of nanofluids.

Rafiq *et al.* [60] observed an enhancement of breakdown voltage by up to about 37% with the highest Fe_3O_4 nanoparticle concentration of 40%. However, further addition of nanoparticles concentration would upset the nanofluid breakdown voltage. On top of that, negative impulse breakdown voltage resulted in degradation as nanoparticles concentration enhanced. Rafiq *et al.* [42] reported improved AC and positive impulse breakdown voltages when utilizing 20 vol.% SiO_2 nanoparticle. However, negative impulse breakdown voltage degrades after adding nanoparticles.

Muangpratoom *et al.* [61] compared the breakdown voltage of pure transformer oil with TiO_2 and $BaTiO_3$ based transformer oil nanofluid at 0.01 and 0.03 vol% nanoparticle loading. Breakdown voltage increased with the rise in temperature. The highest breakdown voltage enhancement, compared with pure transformer oil, was 35% and 37% of 0.03 vol% TiO_2 and $BaTiO_3$, respectively. Muangpratoom and Kunakorn [62] also studied and compared breakdown voltage of pure transformer oil with ZnO based transformer oil at 0.01 and 0.03 vol% nanoparticle concentration.

Yang Ge *et al.* [63] studied various TiO_2 nanoparticle size varying from 5 nm to 15 nm with a fixed 0.075 vol% concentration. It was found that 5 nm, 10 nm and 15 nm powdered

TiO_2 changes to 35 nm, 15 nm and 225 nm, respectively, once dispersed in transformer oil. TiO_2 nanoparticles at 15 nm in transformer oil resulted in the highest breakdown strength increment compared to pure transformer oil, which is by 110%. Chen *et al.* [64] studied and compared breakdown voltage of pure transformer oil with Fe_3O_4, TiO_2 and Al_2O_3 based transformer oil nanofluid. At same nanoparticle concentration, Fe_3O_4, TiO_2 and Al_2O_3 based resulted in 41%, 30% and 7%, respectively, breakdown voltage enhancement compared to pure transformer oil.

Sumathi *et al.* [65] investigated the dielectric strength of hybrid $TiO_2/Al_2O_3/MoS_2$ based transformer oil nanofluid with nanoparticle concentration ranging from 0.01 to 0.1 vol%. Response surface methodology was used to optimize the nanoparticle loadings dispersed in transformer oil. The optimum hybrid nanoparticle concentrations were 0.094 vol. % of Al_2O_3, 0.014 vol% of TiO_2 and 0.097 vol% of MoS_2 and predicted 77.7062 kV/cm of dielectric strength. Confirmation test was performed with the optimum loadings and resulted in 77.02 kV/cm, 0.6862 kV/cm deviation. This optimized hybrid nanoparticle loading resulted in 7.7 times increment than pure transformer oil.

Madavan *et al.* [66] studied and compared various types of natural esters as transformer oil with pure transformer oil. Al_2O_3, BN and Fe_3O_4 nanoparticles were used with volume concentration from 0.05 to 0.5 vol%. Honge oil with 0.05 vol% of Al_2O_3, neem oil with 0.25 vol% of BN, *Punna* oil with 0.5 vol% of BN, *Honge* oil with 0.05 vol% of Fe_3O_4 and neem oil with 0.5 vol% Fe_3O_4 were few of the highest breakdown voltage enhancement. Al_2O_3, BN and Fe_3O_4 resulted enhanced breakdown voltage by up to 36.1%, 47.2% and 50% in transformer oil whereas 30.6%, 29.7% and 31.2% in natural esters.

Du *et al.* [67] synthesized BN based transformer oil with nanoparticle concentration varying from 0.01 to 0.1 wt.%. It was reported that increasing nanoparticle loading enhanced relative permittivity by up to 5.5%. Besides, the dissipation factor decreased with the addition of BN nanoparticles from 0.315% to 0.226%. Breakdown voltage enhanced with the addition of BN nanoparticles by up to 4.3%. Abd-Elhady *et al.* [68] synthesized ZrO_2-based transformer oil with nanoparticle loading from 0.001 to 0.006 wt%. At room temperature, the breakdown voltage enhanced by 202% with 0.001 wt.% of ZrO_2. However, further addition of nanoparticles depleted the breakdown voltage to enhancement by 129%. On the contrary, breakdown voltage enhanced with the rise in temperature from 25% to 143%.

Aberoumand and Jafarimoghaddam [39] synthesized hybrid tungsten oxide-silver nanoparticles that depleted dielectric strength. However, introducing elements such as SiO_2 enhances the electrical insulation property. Ensuring transformer oil nanofluid resulted in breakdown voltage or dielectric strength increment is important for safe operations so that the oil withstand high voltages, generated by the transformer.

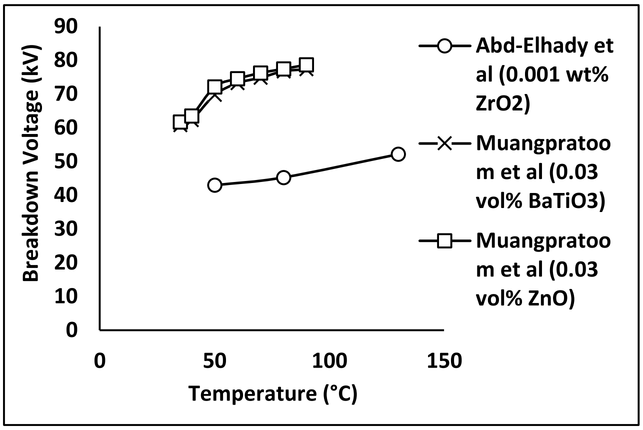


FIGURE 17. **Comparison of breakdown voltage of transformer oil nanofluid against temperature with different nanoparticle type and concentration [56], [57], [63].**

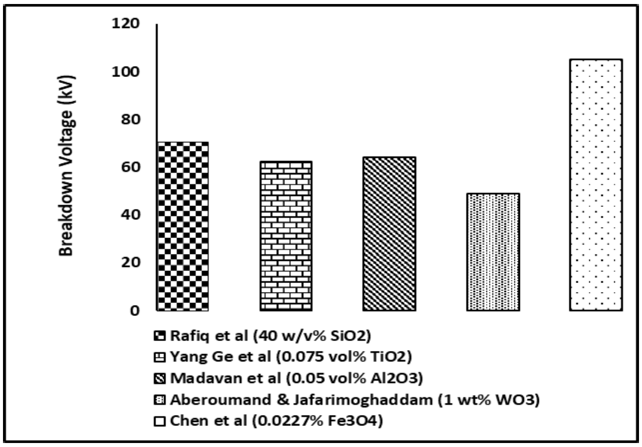


FIGURE 18. **Breakdown voltage comparison with different type of nanoparticles [35], [38], [58], [59], [61].**

Fig 17 displays the comparison of breakdown voltage as a function of temperature. The transformer nanofluid selected showed the highest increment that the researcher investigated. Regardless of the nanoparticle type and concentration, breakdown voltage enhanced with increase in temperature. Muangpratoom *et al.* [61], and Muangpratoom and Kunakorn [62] synthesized ZnO and $BaTiO_3$ based transformer oil nanofluid and reported ZnO-based enhanced higher than $BaTiO_3$-based at the same nanoparticle loading, which is 0.03 vol%. However, the deviation between two transformer oil nanofluids is insignificant. Comparing to Abd-Elhady *et al.* [68], the breakdown voltage of ZnO-based and $BaTiO_3$-based are greater than ZrO_2-based. However, the ZrO_2-based transformer oil was synthesized with nanoparticle loading of 0.001 wt.%.

Fig 18 displays the comparison of breakdown voltage between various types of transformer oil nanofluid. The transformer oil nanofluids were selected based on the highest breakdown voltage achieved by the researchers. Fe_3O_4-based transformer oil, synthesized by Chen et al [64], achieved the highest breakdown voltage compared to other transformer oil nanofluids with 0.0227% concentration. Al_2O_3-based

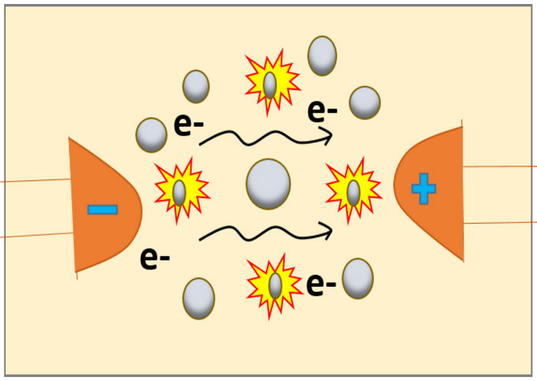


FIGURE 19. Schematic representation of enhanced breakdown voltage of transformer oil after the addition of nanoparticles.

transformer oil, synthesized by Madavan *et al.* [66], was slightly higher than the TiO_2-based transformer oil, synthesized by Yang Ge *et al.* [63]. The difference between these two nanofluids is that Madavan et al dispersed 0.05 vol% Al_2O_3 into *Honge* oil (natural esters) whereas Yang Ge et al dispersed 0.075 vol% TiO_2 into transformer oil. Comparing to the other synthesized nanofluids, Aberoumand & Jafarimoghaddam [39] utilized 1 wt.% WO_3 and resulted in the lowest breakdown voltage.

Researchers observed that the addition of nanoparticles enhanced the breakdown voltage of transformer oil. The nanoparticles acted as scattering obstacles and trap sites in the charge carrier paths, limiting the electrons' mobility (shown in **Fig 19**) [61], [64]. Size of nanoparticles plays a role in enhancing the breakdown voltage of transformer oil nanofluid. Smaller nanoparticle size ensures a greater density of the nanoparticle in the nanofluid than nanoparticle with the larger size for the same concentration. This increases the nanoparticle population to trap free electrons from streamers at a higher rate, leading to higher breakdown strength [70] Besides, nanoparticle type influences the breakdown voltage. For instance, Fe_3O_4-based have higher breakdown voltage due to low relaxation time constant and higher scavenging rate of charges from streamer [66]. However, increasing the volume concentration would deplete the breakdown voltage due alteration of electrodynamic of nanofluids [71].

E. MOISTURE CONTENT

Moisture content would degrade the cooling and insulation effect of the coolant, especially when used in power transformers. High moisture content would degrade insulation of the transformer oil as electrical conduction would likely to occur. However, this parameter was not investigated when synthesizing transformer oil nanofluids.

Menkiti *et al.* [72] utilized *Terminalia catappa* kernel oil as an alternative to mineral transformer oil whereby the kernel oil was synthesized via direct purification and transesterification method. Comparing with two methods, kernel oil that was obtained by transesterification showed the lowest moisture content ranging from 0.9-1.0 mg/kg which agreed to result reported by Usman *et al.* [73]

TABLE 8. Moisture content comparison with different types of nanoparticles dispersed in transformer oil [56], [57].

Oil Type	Moisture Content (ppm)
Mineral Oil (MO)	18.6
MO mixed 0.01 vol% TiO2	17.6
MO mixed 0.01 vol%. BaTiO3	18.5
MO mixed 0.03 vol% TiO2	17.3
MO mixed 0.03 vol%. BaTiO3	18.2
MO mixed 0.01 vol% ZnO with Span 80	19.2
MO mixed 0.01 vol%. ZnO without Span 80	18.9
MO mixed 0.03 vol% ZnO with Span 80	19.5
MO mixed 0.03 vol%. ZnO without Span 80	19.3

TABLE 9. summary of the challenges and future work of transformer oil nanofluids.

Challenges	Future Work
Stability of nanofluid	Stability with respect to temperature for longer duration
Type of nanoparticle	Selection of nanoparticles that promotes thermal conductivity and dielectric strength or breakdown voltage of the overall transformer oil nanofluid
Coolant trait	Study of thermo-physical properties between mineral oil and vegetable oil to highlight its importance as coolant
Blend oil synergy	Selection of vegetable oil to be mixed with mineral oil to improve thermo-physical and dielectric properties
Degradation of oil	Investigation of transformer oil nanofluid degradation to evaluate its shelf life

Sohel Murshed *et al.* [56] and Khedkar *et al.* [57] compared moisture content of pure mineral oil with TiO_2, $BaTiO_3$ and ZnO based mineral oil. Regardless of the nanoparticle concentration and presence of surfactant, there was no significant difference in moisture content, with less than 5% increment. The mineral oil and nanofluids were dried using a vacuum oven before proceeding further analysis. **Table 8** below displays the moisture content of different types of nanoparticles used dispersed in transformer oil.

Presence of moisture content in transformer oil is undesirable but it cannot be removed completely due to the presence of moisture in the atmosphere. Water molecules have high polarity where the oxygen atom tends to be negatively charged while the hydrogen atom tends to be positively charged [74]. Unlike mineral oils, vegetable oil contains fatty acids which is responsible for attracting water molecules which accelerates the aging and degradation processes. Vacuum drying is one of the steps that should be involved during the nanofluid synthesis in order to reduce the moisture content.

V. CONCLUSION, CHALLENGES AND FUTURE WORK

Research works on the stability improvement, thermos-physical and dielectric properties of transformer oil have been conducted but remain challenging and open new window of opportunities for future researchers. The use of nanoparticles has demonstrated interesting traits to enhance these transformer oil properties ranging from fully conductive to insulating nanoparticles. The development of transformer oil could potentially improve the operation of the transformer itself and perhaps reduced machine size or volume overall. Even though such research has been reported and investigated, there are more challenges that have yet to be solved;

- Stability of the transformer oil-based nanofluid was not investigated in detail with respect to temperature and for a longer duration, which limits its application. Preparation of stable nanofluid itself can be achieved through dispersion means. However, dispersing hybrid nanoparticles into a base fluid is a challenge due to particle charge traits.
- Selection of nanoparticle type with enhanced thermal conductivity should possess high dielectric strength or breakdown voltage for excellent insulation
- Study and comparison of thermo-physical properties between mineral oil and vegetable oil to highlight the importance of transformer oil act as a coolant.
- Blend oil research is limited; a mixture of mineral and vegetable oils for good synergy. Vegetable oil has proven to be an environmentally friendly, biodegradable and safer alternative for transformer oil but still, possess weaknesses. Blend oils could result in improved overall properties provided a careful selection of vegetable oil.
- Investigation of transformer oil-based nanofluid degradation is rarely done, which limits further study. Effect of nanoparticle and blend oil concentration on the shelf life of transformer oils is yet to be investigated.

REFERENCES

[1] C. AJ, 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.

[2] M. I. Hasan, "Improving the cooling performance of electrical distribution transformer using transformer oil—Based MEPCM suspension," *Eng. Sci. Technol. Int. J.*, vol. 20, no. 2, pp. 502–510, 2017.

[3] M. J. Heathcote, "Electric power transformer engineering, third edition [book reviews]," *IEEE Power Energy Mag.*, vol. 11, no. 5, pp. 94–95, Sep./Oct. 2013.

[4] L. E. Lundgaard, W. Hansen, D. Linhjell, and T. J. Painter, "Aging of oil-impregnated paper in power transformers," *IEEE Trans. Power Del.*, vol. 19, no. 1, pp. 230–239, Jan. 2004.

[5] H. I. Septyani, I. Arifianto, and A. P. Purnomoadi, "High voltage transformer bushing problems," in *Proc. Int. Conf. Elect. Eng. Inf.*, Jul. 2011, pp. 1–4.

[6] H. R. Sheppard, "A century of progress in electrical insulation 1886-1986," *IEEE Elect. Insul. Mag.*, vol. 2, no. 5, pp. 20–30, Sep. 1986.

[7] G. Mercier, "WEMCOL capacitor fluid development," in *Proc. Elect./Electron. Insul. Conf.*, 1997.

[8] S. Vishal and P. Vikas, "Transformer's history and its insulating oil," in *Proc. 5th Nat. Conf. (INDIACom)*, Mar. 2011.

[9] T. V. Oommen, C. C. Claiborne, and J. T. Mullen, "Biodegradable electrical insulation fluids," in *Proc. Elect. Insul. Conf. Elect. Manuf. Coil Winding Conf.*, Sep. 1997, pp. 465–468.

[10] K. R. Linsley, "Nonflammable small power transformers," in *Proc. Amer. Power Conf.*, Apr. 1981, pp. 2–7.

[11] I. Fofana, V. Wasserberg, H. Borsi, and E. Gockenbach, "Challenge of mixed insulating liquids for use in high-voltage transformers.1. Investigation of mixed liquids," *IEEE Elect. Insul. Mag.*, vol. 18, no. 3, pp. 18–31, May 2002.

[12] R. Murugan and R. Ramasamy, "Understanding the power transformer component failures for health index-based maintenance planning in electric utilities," *Eng. Failure Anal.*, vol. 96, pp. 274–288, Feb. 2019.

[13] M. Wang, A. J. Vandermaar, and K. D. Srivastava, "Review of condition assessment of power transformers in service," *IEEE Elect. Insul. Mag.*, vol. 18, no. 6, pp. 12–25, Nov. 2002.

[14] M. Sefidgaran, M. Mirzaie, and A. Ebrahimzadeh, "Reliability model of the power transformer with ONAF cooling," *Int. J. Elect. Power Energy Syst.*, vol. 35, no. 1, pp. 97–104, Feb. 2012.

[15] L. M. Dumitran, R. Setnescu, P. V. Notingher, L. V. Badicu, and T. Setnescu, "Method for lifetime estimation of power transformer mineral oil," *Fuel*, vol. 117, pp. 756–762, Jan. 2014.

[16] *Temperature Level Analysis*, Delta Transformers Inc., 2009.

[17] "Transformer reliability survey," Cigre Working Group, Tech. Rep. WG A2.37 TB 642, Dec. 2015.

[18] R. Murugan and R. Ramasamy, "Failure analysis of power transformer for effective maintenance planning in electric utilities," *Eng. Failure Anal.*, vol. 55, pp. 182–192, Sep. 2015.

[19] M. Rafiq, Y. Lv, Y. Zhou, K. B. Ma, W. Wang, C. Li, and Q. Wang, "Use of vegetable oils as transformer oils-a review," *Renew. Sustain. Energy Rev.*, vol. 52, pp. 308–324, Dec. 2015.

[20] M. Jovalekic, D. Vukovic, and S. Tenbohlen, "Dissolved gas analysis of alternative dielectric fluids under thermal and electrical stress," in *Proc. IEEE Int. Conf. Dielectric Liquids*, Jun. 2011, pp. 1–4.

[21] Z. Wang, X. Yi, J. Huang, J. V. Hinshaw, and J. Noakhes, "Fault gas generation in natural-ester fluid under localized thermal faults," *IEEE Elect. Insul. Mag.*, vol. 28, no. 6, pp. 45–56, Nov./Dec. 2012.

[22] R. Villarroel, D. F. García, B. García, and J. C. Burgos, "Moisture diffusion coefficients of transformer pressboard insulation impregnated with natural esters," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 22, no. 1, pp. 581–589, Feb. 2015.

[23] A. Susilo, J. Muslim, M. Hikita, M. Kozako, M. Tsuchie, Y. Z. Arief, N. A. Muhamad, T. Suzuki, S. Hatada, A. Kanetani, T. Kano, Suwarno, and U. Khayam, "Comparative study of partial discharge characteristics and dissolved gas analysis on palm-based oil as insulating material," in *Proc. 2nd IEEE Conf. Power Eng. Renew. Energy (ICPERE)*, Dec. 2014, pp. 232–236.

[24] Y. Z. Arief, S. A. Azli, N. A. Muhamad, and N. Bashir, "The effect of electrical ageing on electrical properties of palm fatty acid ester (PFAE) and FR3 as dielectric materials," in *Proc. IEEE Student Conf. Res. Develpoment*, Dec. 2013, pp. 209–214.

[25] T. Toudja, F. Chetibi, A. Beldjilali, H. Moulai, and A. Beroual, "Electrical and physicochemical properties of mineral and vegetable oils mixtures," in *Proc. IEEE 18th Int. Conf. Dielectric Liquids (ICDL)*, vol. 617, Jun./Jul. 2014, pp. 3–6.

[26] Y. Hiramatsu, K. Kamidani, and Y. Muramoto, "Effect of water on AC breakdown properties of vegetable-oil-based insulating fluid mixed with mineral oil," in *Proc. Int. Symp. Elect. Insulating Mater. (ISEIM)*, Sep. 2017, pp. 211–214.

[27] H. Yu, R. Chen, X. Hu, X. Xu, and Y. Xu, "Dielectric and physicochemical properties of mineral and vegetable oils mixtures," in *Proc. ICDL*, Jun. 2017, pp. 29–32.

[28] S. Li, X. Zhao, R. Liao, L. Yang, and P. Guo, "Study on ageing characteristics of insulating pressboard impregnated by mineral-vegetable oil," in *Proc. IEEE Conf. Elect. Insul. Dielectric Phenomena (CEIDP)*, Oct. 2016, pp. 70–73.

[29] A. Johari, A. A. Suleiman, N. Bashir, N. A. Muhamad, M. H. Ahmad, and I. M. Inuwa, "Performance of biodegradable insulating oil under accelerated thermal ageing," in *Proc. IEEE Int. Conf. Power Energy (PECon)*, Dec. 2014, pp. 9–12.

[30] F. Guerbas, L. Adjaout, A. Abada, and D. Rahal, "Thermal aging effect on the properties of new and reclaimed transformer oil," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl. (ICHVE)*, Sep. 2016, pp. 16–19.

[31] M. Takasago and K. Takaoka, "Analysis of the state of dissolved water in methyldecanoate and safflower oil by FT-near infrared spectrometry," *J. Jpn. Oil Chem. Soc.*, vol. 33, no. 11, pp. 772–775, 1984.

[32] S. Itahashi, H. Mitsui, and M. Sone, "State of dissolved water in insulating oil under electric field," *IEEJ Trans. Inst. Elect. Eng. Jpn.*, vol. 115, no. 9, pp. 896–902, 1995.

[33] Z. H. Shah and Q. A. Tahir, "Dielectric properties of vegetable oils," *J. Sci. Res.*, vol. 3, no. 3, pp. 481–492, Aug. 2011.

[34] W. Yu and H. Xie, "A review on nanofluids: Preparation, stability mechanisms, and applications," *J. Nanomater.*, vol. 2012, Jul. 2011, Art. no. 435873.

[35] P. Kopčanský, L. Tomčo, K. Marton, M. Koneracká, M. Timko, and I. Potočová, "The DC dielectric breakdown strength of magnetic fluids based on transformer oil," *J. Magn. Magn. Mater.*, vol. 289, pp. 415–418, Mar. 2005.

[36] 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.

[37] 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, 2008.

[38] 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, no. 5, pp. 140–152, Feb. 2016.

[39] S. Aberoumand and A. Jafarimoghaddam, "Tungsten (III) oxide (WO_3)—Silver/transformer oil hybrid nanofluid: Preparation, stability, thermal conductivity and dielectric strength," *Alexandria Eng. J.*, vol. 57, pp. 169–174, Mar. 2018.

[40] 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.

[41] J. Ghasemi, S. Jafarmadar, and M. Nazari, "Effect of magnetic nanoparticles on the lightning impulse breakdown voltage of transformer oil," *J. Magn. Magn. Mater.*, vol. 389, pp. 148–152, Sep. 2015.

[42] M. Rafiq, C. Li, Q. Du, Y. Lv, and K. Yi, "Effect of SiO_2 nanoparticle on insulating breakdown properties of transformer oil," in *Proc. IEEE Int. Conf. High Volt. Eng. Appl. (ICHVE)*, Sep. 2016, pp. 1–4.

[43] M. M. Bhunia, S. Das, P. Chattopadhyay, S. Das, and K. K. Chattopadhyay, "Enhancement of thermal conductivity of transformer oil by exfoliated white graphene nanosheets," in *Proc. Int. Conf. Environ. Elect. Eng. (EEEIC)*, Jun. 2016, pp. 1–5.

[44] S. U. Ilyas, R. Pendyala, M. Narahari, and L. Susin, "Stability, rheology and thermal analysis of functionalized alumina- thermal oil-based nanofluids for advanced cooling systems," *Energy Convers. Manag.*, vol. 142, pp. 215–229, Jun. 2017.

[45] A. Cavallini, R. Karthik, and F. Negri, "The effect of magnetite, graphene oxide and silicone oxide nanoparticles on dielectric withstand characteristics of mineral oil," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2592–2600, Oct. 2015.

[46] S. H. Qing, W. Rashmi, M. Khalid, T. C. S. M. Gupta, M. Nabipoor, and M. T. Hajibeigy, "Thermal conductivity and electrical properties of Hybrid SiO_2-graphene naphthenic mineral oil nanofluid as potential transformer oil," *Mater. Res. Express*, vol. 4, no. 1, 2017, Art. no. 015504.

[47] J. Taha-Tijerina, T. N. Narayanan, G. Gao, M. Rohde, D. A. Tsentalovich, M. Pasquali, and P. M. Ajayan, "Electrically insulating thermal nano-oils using 2D fillers," *Amer. Chem. Soc. Nano*, vol. 6, no. 2, pp. 1214–1220, 2012.

[48] Y. Liu, Y. Liu, P. Hu, X. Li, R. Gao, Q. Peng, and L. Wei, "The effects of graphene oxide nanosheets and ultrasonic oscillation on the supercooling and nucleation behavior of nanofluids PCMs," *Microfluid. Nanofluidics*, vol. 18, no. 1, pp. 81–89, Jan. 2015.

[49] J. Li, K. Yu, K. Qian, H. Cao, X. Lu, and J. Sun, "The situ preparation of silica nanoparticles on the surface of functionalized graphene nanoplatelets," *Nanosc. Res. Lett.*, vol. 9, no. 1, Apr. 2014, Art. no. 172.

[50] D. W. Johnson, B. P. Dobson, and K. S. Coleman, "A manufacturing perspective on graphene dispersions," *Current Opinion Colloid Interface Sci.*, vol. 20, nos. 5–6, pp. 367–382, 2015.

[51] J. Taha-Tijerina, N. C.-de La Peña, C. Rivera-Solorio, and R. Cue-Sampedro, "Thermo-physical evaluation of dielectric mineral oil-based nitride and oxide nanofluids for thermal transport applications," *J. Therm. Sci. Technol.*, vol. 14, no. 1, pp. 1–8, 2019.

[52] B. C. Pak and Y. I. Cho, "Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles," *Exp. Heat Transf.*, vol. 11, no. 2, pp. 151–170, Apr. 1998.

[53] D. D. H. Fontes, G. Ribatski, and E. P. B. Filho, "Experimental evaluation of thermal conductivity, viscosity and breakdown voltage AC of nanofluids of carbon nanotubes and diamond in transformer oil," *Diamond Rel. Mater.*, vol. 58, pp. 115–121, Sep. 2015.

[54] D. Berman, A. Erdemir, and A. V. Sumant, "Graphene: A new emerging lubricant," *MaterialsToday*, vol. 17, no. 1, pp. 31–42, Jan./Feb. 2014.

[55] F. A. Riveland, "Investigation of nanoparticles for enhanced filtration properties of drilling fluid," Inst. Petroleum Eng. Appl. Geophys., Tech. Rep., 2013.

[56] S. M. S. Murshed, S.-H. Tan, and N.-T. Nguyen, "Temperature dependence of interfacial properties and viscosity of nanofluids for droplet-based microfluidics," *J. Phys. D., Appl. Phys.*, vol. 41, no. 8, Apr. 2008, Art. no. 085502.

[57] R. S. Khedkar, A. S. Kiran, S. S. Sonawane, K. Wasewar, and S. S. Umre, "Thermo—Physical characterization of paraffin based Fe_3O_4 nanofluids," *Procedia Eng.*, vol. 51, pp. 342–346, Jan. 2013.

[58] M. Rafiq, Y. Lv, and C. Li, "A review on properties, opportunities, and challenges of transformer oil-based nanofluids," *J. Nanomater.*, vol. 2016, May 2016, Art. no. 8371560.

[59] H. J. Wang, S. J. Ma, H. M. Yu, Q. Zhang, C. M. Guo, and P. Wang, "Thermal conductivity of transformer oil from 253 k to 363 K," *Petroleum Sci. Technol.*, vol. 32, no. 17, pp. 2143–2150, 2014.

[60] M. Rafiq, C. Li, Y. Ge, Y. Lv, and K. Yi, "Effect of Fe_3O_4 nanoparticle concentrations on dielectric property of transformer oil," in *Proc. IEEE Int. Conf. High Volt. Eng. Appl.*, Sep. 2016, pp. 1–4.

[61] 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. Elect. Eng./Electron., Comput., Telecommun. Inf. Technol. (ECTI-CON)*, Jul. 2018, pp. 536–539.

[62] P. Muangpratoom, N. Pattanadech, W. Vittayakorn, K. Thungsook, and A. Kunakorn, "Dielectric properties of mineral oil-based nanofluids using zinc oxide Nano-composites for power transformer application," in *Proc. Condition Monit. Diagnosis*, Sep. 2018, pp. 1–4.

[63] Y. Ge, M. Niu, L. Wang, M. Huang, Y. Lv, and J. Yuan, "Effects of TiO_2 nanoparticle size on dielectric properties of transformer oil," in *Proc. IEEE Conf. Elect. Insul. Dielectr. Phenomena*, Oct. 2018, pp. 136–139.

[64] C. Chen, M. Niu, L. Wang, Y. Ge, M. Huang, Y. Lv, and C. Li, "Effect of nanoparticle type on prebreakdown and breakdown characteristics of transformer oil," in *Proc. IEEE 2nd Int. Conf. Dielectr.*, Jul. 2018, pp. 1–4.

[65] S. Sumathi, S. Rajesh, and P. Subburaj, "Investigation of dielectric strength of transformer oil based on hybrid TiO_2/Al_2O_3/MoS_2 nanofluid using Taguchi and response surface methodology," *IETE J. Res.*, Jan. 2019.

[66] R. Madavan, S. S. Kumar, and M. W. Iruthyarajan, "A comparative investigation on effects of nanoparticles on characteristics of natural esters-based nanofluids," *Colloids Surf. A, Physicochem. Eng. Aspects*, vol. 556, pp. 30–36, Nov. 2018.

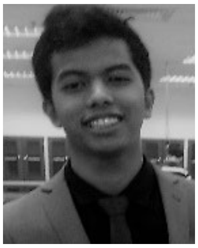
[67] B. X. Du and X. L. Li, "High thermal conductivity transformer oil filled with BN nanoparticles," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 2, pp. 851–858, Apr. 2015.

[68] A. M. Abd-Elhady, M. E. Ibrahim, T. A. Taha, and M. A. Izzularab, "Effect of temperature on AC breakdown voltage of nanofilled transformer oil," *IET Sci., Meas. Technol.*, vol. 12, no. 1, pp. 138–144, 2017.

[69] Y.-F. Du, Y.-Z. Lv, Z. Jian-Quan, X.-X. Li, and C.-R. Li, "Breakdown properties of transformer oil-based TiO_2 nanofluid," in *Proc. Annu. Rep. Conf. Elect. Insul. Dielectic Phenomena*, Oct. 2010, pp. 1–4.

[70] R. Madavan and S. Balaraman, "Investigation on effects of different types of nanoparticles on critical parameters of nano-liquid insulation systems," *J. Mol. Liq.*, vol. 230, pp. 437–444, Mar. 2017.

[71] A. Katiyar, P. Dhar, T. Nandi, and S. K. Das, "Effects of nanostructure permittivity and dimensions on the increased dielectric strength of nano insulating oils," *Colloids Surfaces A, Physicochem. Eng. Aspects*, vol. 509, pp. 235–243, Nov. 2016.
[72] M. C. Menkiti, C. M. Agu, P. M. Ejikeme, and O. E. Onyelucheya, "Chemically improved *Terminalia catappa* L. oil: A possible renewable substitute for conventional mineral transformer oil," *J. Environ. Chem. Eng.*, vol. 5, no. 1, pp. 1107–1118, 2017.
[73] M. A. Usman, O. O. Olanipekun, and U. T. Henshaw, "A comparative study of soya bean oil and palm kernel oil as alternatives to transformer oil," *J. Emerg. Trends Eng. Appl. Sci.*, vol. 3, no. 1, pp. 33–37, 2012.
[74] M. K. Campbell and S. O. Farrell, *Biochemistry*. Pacific Grove, CA, USA: Brooks/Cole, 2006.



DANIAL AMIN was born in Kuala Lumpur, Malaysia, in 1995. He received the B.Eng. degree in chemical engineering from Taylor's University, Malaysia, in 2017, where he is currently pursuing the M.Sc. degree in engineering. From December 2015 to March 2016, he underwent an internship program in Top Glove Sdn. Bhd, Malaysia. He was assigned as an Industrial Trainee with the Research and Development Department.

RASHMI WALVEKAR received the bachelor's degree in chemical engineering from the SDM College of Engineering and Technology, Dharwad, India, in 2004, and the M.Sc. degree in chemical and environmental engineering from University Putra Malaysia, with a focus on CFD simulations of oil-water dispersed flows in pipelines, where she is currently pursuing the Ph.D. degree in nanofluids for heat transfer application. She is currently an Associate Professor with the Department of Chemical Engineering, Taylors University, Malaysia. Her research interests include nanofluids, nanolubricants, and deep eutectic solvents for energy storage and harvesting. She was a recipient of Vice-Chancellor most cited Academic Award by Taylor's University and Best Paper Award at International conference on applied science and technology and International technology congress. She is also a Chartered Chemical Engineer and Chartered Member of the Institution of Chemical Engineers (IChemE), U.K.

MOHAMMAD KHALID received the bachelor's degree in chemical engineering from Visvesvaraya Technological University, India, and the M.Sc. degree in chemical and environmental engineering from Universiti Putra Malaysia. He is currently pursuing the Ph.D. degree with International Islamic University, Malaysia, with a focus on developing radiation crosslinked rubber nanocomposites. He is currently a Full Professor and the Head of the Graphene and Advanced 2D Materials Research Group, Sunway University, Malaysia. He is currently working on solar energy harvesting using deep eutectic salts (DES), carbon nanoparticles-based nanolubricants for improving engine performance and supercapattery devices for energy storage. He has published more than 100 articles in international journals and refereed international conferences, five patents, and seven chapters in books. His research interests include 2D material synthesis, heat transfer fluids, phase change materials, energy harvesting, conversion, and storage He is also a Chartered Member of the Institution of Chemical Engineers (MIChemE) and Fellow of Higher Education Academy (FHEA), U.K.

MAHESH VAKA was born in Tenali, India, in 1990. He received the bachelor's degree from Sathyabama University, with a focus on nanotechnology, and the master's degree from Deakin University, Australia, with a focus on graphene and graphene hybrid derivatives for sensor applications. He is currently pursuing the Ph.D. degree in chemical engineering at Taylor's University, Malaysia. His current research interest includes the synthesis of 2D nanomaterials and its application in solar energy harvesting and storage.

NABISAB MUJAWAR MUBARAK received the B.E. degree in chemical engineering from Visvesvaraya Technological University, India, the M.Sc. degree in engineering from International Islamic University, Malaysia, with the specialization in nanotechnology, and the Ph.D. degree (Hons.) in chemical engineering from the University of Malaya. He is currently an Associate Professor and the Faculty of Engineering and Science, Curtin University, Malaysia. He serves as a Scientific Reviewer in numerous journals *Chemical Engineering and Nano Technology*. He has published more than 100 journal articles, 20 conference proceedings and authored eight book chapters. His research outputs also include seven patent filings and 21 research awards. His research interests include synthesis of biofuel using microwave heating, protein purification using CNTs, wastewater treatment, separation process and thermodynamics, and advanced material and reaction engineering. He is also a Fellow Member and a Chartered Professional Engineer with the Institution of Engineers, Australia, and a Chartered Chemical Engineer with the Institution of Chemical Engineers, U.K. He was awarded the Outstanding Scientist in publication and citation by I proclaim Malaysia, in 2017 and the Outstanding Faculty of Chemical Engineering, in 2018, and the Best Scientific Research Award London 2018 by ASDF.

T. C. S. M. GUPTA was born in Pippara, India, in 1965. He received the M.Sc. degree in chemistry from the University of Roorkee, in 1987 and the Ph.D. degree in refining chemistry from the Indian Institute of Petroleum, Dehradun, India, HNB Garhwal University, in 1992. He was a Formulation Laboratory In-Charge with ATIC Industries Limited (ATUL-ICI Joint Venture), Gujarat, from 1992 to 1996. He joined Apar Industries Limited, Mumbai, in 1996 as a Manager of the laboratory and rose through ranks as the Vice President-Operations. He was an Operations Manager with A.C. Lubricants Sdn. Bhd, Malaysia, for seven years, from 2003 to 2006 and 2011 to 2015 and the Chief Operating Officer with Lube World Sdn. Bhd., Malaysia. He has been a Senior Vice President-R&D, Quality and Technical, since 2015. He takes active interest in academic research and has coauthored about 35 articles, filed two Indian Patents and published six Technical reports. As an Industrial Research Scientist, his research interests include petroleum refining, lubricant and additives, and Nano fluids for lubricant applications and specialty oils. He has traveled extensively across the globe and is an Active Member of several research groups. He is curretnly a member of BIS committees in ETD 3, PCD 25, and various Cigre working groups, ALMU, Singapore and Quality Forum of India. He has co-supervised Masters and Ph.D. students and is an approved co-super visor/Examiner with the University of Nottingham, Taylors University, Malaysia, Dharmsinh Desai University, Nadiad, Gujarat, and the Institute of Chemical Technology, Mumbai. He served as an Industry Advisory Panel (IAP) Member with Taylor's University, Malaysia. He received the merit scholarship as a Senior Research Fellow and a Research Associate from the Indian Institute of Petroleum, Dehradun.

• • •