



Investigation on Dielectric Insulation and Improvement of Thermal Properties of TiO₂-based Nanofluids with Carbon Quantum Dot Surface Functionalization

P. Kasi Viswanathan^{1*} and S. Chandrasekar²

¹Department of Electrical and Electronic Engineering, Dayananda Sagar Academy of Technology and Management, Bangalore, KA, India

²Department of Electrical and Electronic Engineering, Sona PERT R&D Centre, Sona College of Technology, Salem, TN, India

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*kasiviswap@gmail.com



ABSTRACT

Advanced dielectric fluids with improved thermal and electrical insulation are needed for the operation of stationary power systems, hybrid electric vehicle technology and pulse power generation systems. The present commercial dielectric fluids do not meet the stringent demands required for these technologies to optimise energy efficiency and system reliability. In this research, Carbon Quantum Dots (CQDs) were used to modify the surface of titanium nanomaterials to enhance both their dielectric and thermal properties. To optimise the dielectric properties, we selectively coated CQDs onto the titanium nanomaterials with tailored dielectric constants to determine their dielectric constant, loss factor, capacitance, volume resistivity, flash point, fire point, and viscosity. Three different concentration ratios of functionalized nanomaterials (mass fractions of 0.01%, 0.05%, and 0.1%) in mineral oil were used to prepare three different types of nanofluids for evaluation. The results show there was an increase in breakdown strength (up to 15-20kV), dielectric constant (10-15%) and volume resistivity (from $1 \times 10^{13} \Omega \cdot \text{cm}$ to $4.5 \times 10^{13} \Omega \cdot \text{cm}$). The loss factor reduced to 0.001 from 0.007. Additionally, the evaluation showed that the functionalized nanomaterials significantly increased the flash and fire points of the nanofluids by 10-19°C. Surface functionalization using CQDs promotes uniform nanoparticle dispersion and stabilizes interfacial charge polarization and relaxation processes. These effects collectively contribute to an increase in relative permittivity, a lower loss factor, and sustained capacitance behavior in the dielectric system.

Keywords: Mineral oil; Nanofluid; Breakdown voltage; Dielectric liquids; Insulation; Titanium oxide nanoparticles.

1. INTRODUCTION

The dielectric insulation materials constitute a critical technological foundation for modern electrical and electronic systems, as their electrical, thermal, and chemical stability governs the reliability and operational safety of power equipment under high-voltage and high-temperature conditions. Conventional insulating media such as mineral oils and polymer-based dielectrics have been widely employed due to their favourable dielectric strength, chemical stability, and cost-effectiveness (Karataş *et al.* 2022; Stone *et al.* 2005). However, their long-term performance is constrained by thermal-oxidative ageing and the accumulation of contaminants, limiting their applicability in advanced power and energy systems (Chandrasekar *et al.* 2014; Suhaimi *et al.* 2020). Consequently, the development of enhanced insulation materials remains an important research focus.

The dielectric performance of insulating materials is primarily governed by their polarisation mechanisms, which are commonly assessed using parameters such as dielectric constant, resistivity, and dielectric loss. Polar dielectrics, characterised by asymmetric molecular structures and intrinsic dipole moments, exhibit strong field-dependent polarisation. However, they are highly sensitive to moisture ingress and temperature variations, leading to increased dielectric constant and reduced resistivity (Rafiq *et al.* 2023; Haque *et al.* 2021).

In contrast, nonpolar dielectrics possess symmetric covalent bonding, resulting in high electrical resistivity but relatively low dielectric constants.

Exposure to environmental stressors such as humidity, oxidation, and gas absorption progressively degrades dielectric materials, causing increased leakage currents and insulation failure (Koch *et al.* 2010; Abdi *et al.* 2025; Bojovschi *et al.* 2019). The degradation process is driven by multiple mechanisms including charge trapping, ionic migration, oxidative reactions, and moisture diffusion, which collectively alter permittivity, dissipation factor, and electrical resistivity (Küchler, 2018; Yoon *et al.* 2023; Lundgaard *et al.* 2004; Xue *et al.* 2021). These processes significantly reduce the service life and reliability of insulation systems in power equipment.

In liquid insulation systems, particularly mineral oils and natural esters, oxidation by-products and contaminants precipitate over time to form insulating sludge. This sludge accumulates on solid insulation surfaces, obstructing heat dissipation and accelerating thermal runaway, partial discharge activity, and dielectric ageing (Szcześniak and Przybyłek, 2021; Fofana *et al.* 2010). Additionally, the presence of polar degradation products increases fluid permittivity and conductivity, leading to higher dielectric losses, increased acidity, and reduced breakdown voltage. Such degradation can be quantitatively monitored through dielectric parameters

including volume resistivity, relative permittivity, and temperature-dependent relaxation behaviour (Xia *et al.* 2017; Saini and Harid, 2023; Djurovic *et al.* 2023).

To overcome the limitations of conventional insulating liquids, dielectric nanofluids have emerged as promising alternatives, offering improved breakdown strength, thermal conductivity, and ageing resistance. These improvements arise from enhanced charge dissipation and interfacial polarisation control (Danial *et al.* 2019; Parekh *et al.* 2025). However, the practical realization of dielectric nanofluids is hindered by persistent challenges related to nanoparticle agglomeration and long-term dispersion instability. High surface energy and strong van der Waals forces promote clustering, sedimentation, and non-uniform electric field distribution within the fluid (Wu *et al.* 2024; Salah *et al.* 2022; Girish *et al.* 2025).

Nanoparticle agglomeration adversely affects both dielectric and thermal performance, negating the benefits of nanoscale interfacial phenomena. Surface functionalization of nanofillers has therefore been widely investigated as an effective strategy to improve dispersion stability and physicochemical compatibility with the host liquid. Studies have reported enhanced dielectric strength in silane-treated SiO₂ nanofluids (Zhang *et al.* 2023), improved stability of oleic-acid-modified TiO₂ nanoparticles in transformer oil (Lv *et al.* 2016), and increased breakdown voltage in surface-treated Fe₃O₄ nanoparticles dispersed in natural ester fluids due to improved interfacial bonding (Lytikova *et al.* 2021).

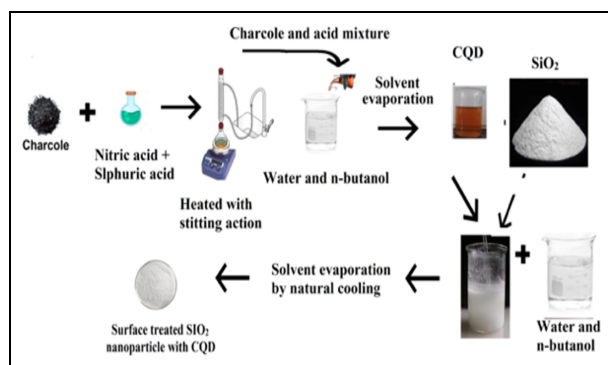


Fig. 1: Schematic representation of nanofluid preparation processes

Recent research has increasingly focused on carbon-based nanomaterials as functional additives in dielectric nanofluids. Among these, Carbon Quantum Dots (CQDs) (Kong *et al.* 2024; Dsouza *et al.* 2021), typically less than 10 nm in size, exhibit unique properties including quantum confinement effects, abundant surface functional groups, and tunable hydrophilic–hydrophobic surface chemistry (Li *et al.* 2025; Bibi *et al.* 2024). These attributes promote strong interfacial interactions with metal oxide nanoparticles and enhance colloidal stability, thereby suppressing agglomeration and mitigating dielectric degradation (Palanisamy *et al.* 2020; Palanisamy *et al.* 2022; Mansour *et al.* 2019).

Despite the demonstrated potential of CQDs and surface-functionalized nanofillers (Viswanathan *et al.* 2019a; Viswanathan *et al.* 2019b), systematic investigations combining CQD functionalization with TiO₂ nanoparticles for dielectric

insulation applications remain limited. In particular, the role of CQD-assisted surface modification in suppressing agglomeration-driven dielectric degradation has not been fully explored. Addressing this gap, the present study investigates CQD–functionalized TiO₂ nanofluids, focusing on their dielectric and thermal performance. The breakdown voltage is analyzed using Weibull statistics, along with dielectric constant, loss factor, volume resistivity, and key thermal properties such as flash point, fire point, and viscosity. The proposed approach aims to develop a stable and reliable dielectric nanofluid with improved insulation performance for transformer and high-voltage energy storage applications.

2. SAMPLE PREPARATION AND TEST SETUP

2.1 Preparation of Nanofluid Samples

The prepared CQD solution was used for the surface treatment of titanium oxide nanomaterial by the following processes: 10 g of TiO₂ was weighed and added to 2 g of CQD (a ratio of 5:1 CQD: TiO₂ was maintained for the complete sample preparation processes). The above solution was mixed with water and n-butanol, and subjected to constant stirring processes for around 2 hours. Then, the prepared sample was filtered and dried until the solvent evaporated at room temperature. The sediment was collected. The nanofluids were prepared by adding the above solution to TRANSOL brand mineral oil (base oil) (Fig. 1). Different fluids prepared in the present work are reported in Table 1.

2.2 Characterization Techniques

FESEM of TiO₂ dispersed in insulating liquids is considered vital in the explanation of the relationship between morphology of nanoparticles and dielectric behaviour. Field-Emission Scanning Electron Microscopy offers high-resolution imagery, to understand size of particles, their surface texture, agglomeration structures, and uniformity of distribution. Fourier transform infrared (FTIR) spectroscopy is utilised to get the functional groups and the chemical interaction taking place between the TiO₂ nanoparticles with the carbon quantum dots. Physico-chemical properties of CQD and TiO₂ nanofillers are shown in Table 2.

2.3 Measurements of tan δ , Volume Resistivity, Dielectric Constant and Capacitance

Test sample tan δ , volume resistivity, dielectric constant, and capacitance were measured using a 50 Hz test frequency as per IEC 60247. Tan δ is a measure of real power lost through dielectric insulation materials. The comparison of the measured tan δ value to a known reference value is used to determine the degree of dissipation in the material being tested. Volume resistivity is determined by the applied voltage gradient. Therefore, the longer the time the insulation material is subjected to the applied voltage, the higher the volume resistivity. An Eltel AC 50 Hz test instrument, along with a 500 V AC supply, was utilised to obtain tan δ values. A 500 V DC supply was used to obtain the volume resistivity readings. To observe changes in the test sample as temperature increases, tan δ , dielectric constant,

capacitance, and volume resistivity measurements were obtained at various temperatures (room temperature = 30°C, 50°C, 70°C, 90°C, and 110°C). The setup utilised to perform these tests is shown in Fig. 2

Table 1. Acronyms and concentration of nanofillers

Base Oil	Type of Nano filler Added	% of Filler Added	Sample Acronym
Mineral oil	-	-	MO
	TiO ₂	0.01%wt	T1
		0.05%wt	T2
		0.1%wt	T3
	CQD-TiO ₂	0.01%wt	C1
		0.05%wt	C2
		0.1%wt	C3

Table 2. Properties of nanofillers

	CQD	TiO ₂	CQD-TiO ₂
Purity	>99%	>99.7 %	>99.5 %
Color	Black	White	White
Nature of materials	Graphitic carbon	Amorphous	Amorphous
Type of materials	Insulating	Semiconductor	Semiconductor
Size	2.5 nm	10-30 nm	15-40 nm
Shape	Spherical dot	Nanospheres	White
Specific surface area	~210 (m ² /g)	~98.2-174 (m ² /g)	~150-280 (m ² /g)



Fig. 2: Setup for measurement of dielectric constant, loss factor and volume resistivity

2.4 Flash Point, Fire Points and Volume Viscosity

The flashpoint is the lowest temperature at which a liquid's vapour combination ignites when it

comes into contact with an igniting flame. The fire point is the lowest temperature at which the mixture of air and vapour on the liquid surface ignites and maintains flame even after the ignition source is withdrawn (ASTM D92 / D93). Fig. 3(a) shows the test apparatus used to measure the flash and fire points. Flash and fire points of a fluid were tested using standardized open-cup apparatus. The fluid was gradually heated, and an ignition source was periodically passed over its surface. The temperature at which a brief flame appears was recorded as the flash point, while the temperature at which sustained burning occurs was noted as the fire point. Thermometers attached to the oil-filled test cell were used to detect the temperature rise occurring when 50 mL of the test specimen was heated under controlled test circumstances.

A Redwood viscometer was used to measure viscosity as seen in Fig. 3(b). Oil containers were used to hold the test sample oil, which was then heated using a water bath surrounding the oil container. The ball valve of the orifice tube was opened when the temperature of the bath and container reached the desired level.



Fig. 3: Experimental setup for measuring (a) flash point/fire point and (b) viscosity

The liquid was then allowed to flow to gather 50 mL of liquid samples, and the amount of time needed to do so was recorded. The kinematic viscosity of test samples was determined by measuring the time required. Since viscosity is a temperature-dependent property and rising temperatures can reduce a fluid's viscosity, a thorough investigation of the temperature dependency of viscosity was conducted by measuring viscosity at different test temperatures.

2.5 AC Breakdown Voltage Test (BDV)

The breakdown voltage is the minimum voltage at which an insulating material starts to conduct significantly, leading to failure through ion or electron stream formation. The primary factor to be determined from the BDV is the strength of the insulation material. In this work, a BDV test cell (Fig. 4) with brass mushroom electrodes was used to evaluate the BDV of various concentrations of insulation materials. Two different gap distances (2.5 mm and 5.0 mm) were determined between the electrodes. The BDV test cell

was placed in a BDV test apparatus that has a rating of 100 kV and slowly increased the voltage in the test cell until breakdown occurred between the electrodes. Each test was repeated 10 times, and each sample concentration was evaluated 10 times. The test was conducted at room temperature as per the IEC 60156 standard.



Fig. 4: BDV test setup with electrode configuration

3. RESULTS AND DISCUSSION

3.1 Characterization of Carbon Quantum Dots Treated Nanomaterial

The FESEM images of TiO_2 nanoparticles after CQD coverage are shown in Fig. 5. The magnification scale shown is 500 nm, and the accelerating voltage is 20 kV. There are no significant clusters in the size-controlled distribution of either TiO_2 or CQD- TiO_2 nanoparticles. Measurements show that the average size of TiO_2 particles is between 20 and 30 nm. However, since carbon quantum dots are very small (around 2.5 nm), it is hard to see any noticeable changes in the size and shape of TiO_2 nanoparticles after CQD coverage.

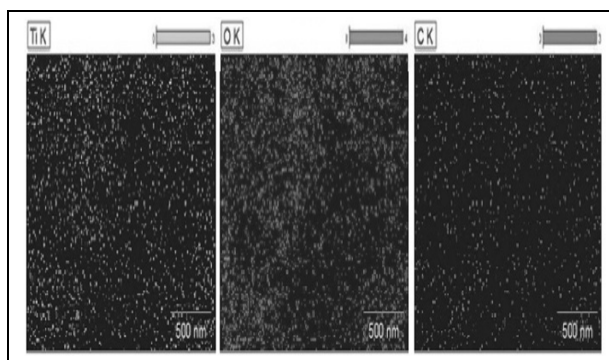


Fig. 5: FESEM images of TiO_2 nanoparticles before and after CQD coverage

Fig. 6 shows the FTIR spectra of pure TiO_2 and CQD-treated TiO_2 nanoparticles. The spectra obtained with the FTIR provide evidence of surface modification and the associated bonding due to the CQD treatment. As indicated above, when CQDs modify the surface of TiO_2 ,

it will exhibit additional peaks or a shift in wavenumbers, indicating that the modification was successful. The intense peak below $600\sim600\text{ cm}^{-1}$ corresponds to Ti-O-Ti stretching modes characteristic of the anatase/rutile lattice. In the CQD-treated TiO_2 , this peak is retained but often appears slightly broadened or shifted, indicating preservation of the TiO_2 crystal framework with modified surface bonding due to CQD attachment. Compared with bare TiO_2 , the CQD-treated sample shows additional or intensified peaks in this region. Peaks around ~1000 to 1200 cm^{-1} are commonly assigned to C-N or symmetric COO stretching vibrations (León *et al.* 2017). The appearance of these features confirms the presence of oxygen- and nitrogen-containing functional groups originating from CQDs and indicates chemical interaction (e.g., Ti-O-C or coordinated carboxylate bonding) at the TiO_2 -CQD interface. These changes also indicate effective functionalization of the surface, leading to improved light absorption and increased surface activity of the composite material.

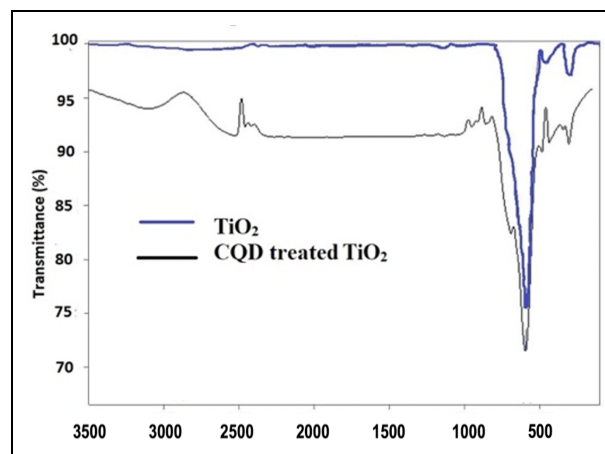


Fig. 6: FTIR spectrum of TiO_2 and CQD- TiO_2 particles

3.2 Breakdown Strength Observations

Results of the breakdown strength tests of the semi-sphere gap electrode for the test fluids are summarized in Fig. 7. The breakdown voltage increases as the electrode distance d increases, although the rate of increase becomes more gradual at larger separations. The standard deviations range from $\pm 5\text{ kV}$ to $\pm 10\text{ kV}$. The breakdown strength of nanofluids is higher than that of pure samples without nanofillers. Adding TiO_2 nanofillers can improve dielectric strength. The increase in breakdown voltage progresses as the concentration of nanofillers increases, reaching slight saturation when moving from 0.05% to 0.1% wt. Among the samples, the CQD-treated nanofluids show better results than the non-treated ones. In the case of CQD samples, the breakdown voltage increases significantly when comparing 0.01 and 0.05% wt concentrations. However, it reaches slight saturation if the concentration increases from 0.05% wt to 0.1% wt. The CQD-treated samples exhibit an improvement of 8–

10 kV at every concentration compared to non-CQD samples.

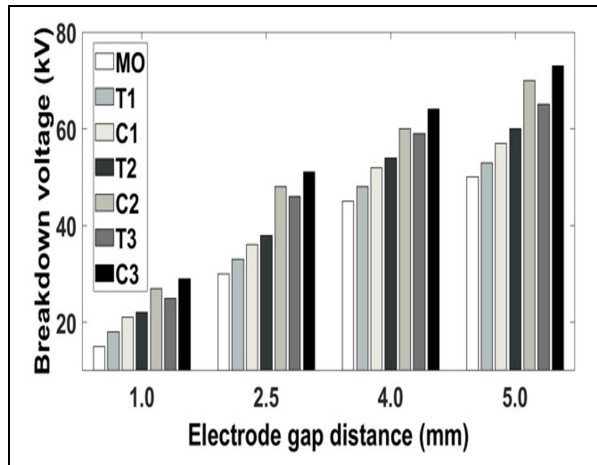


Fig. 7: BDV test results at various electrode gap distances

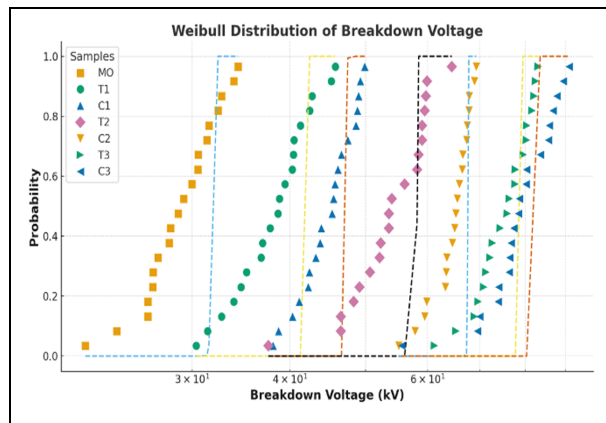


Fig. 8: Weibull distribution of breakdown voltages

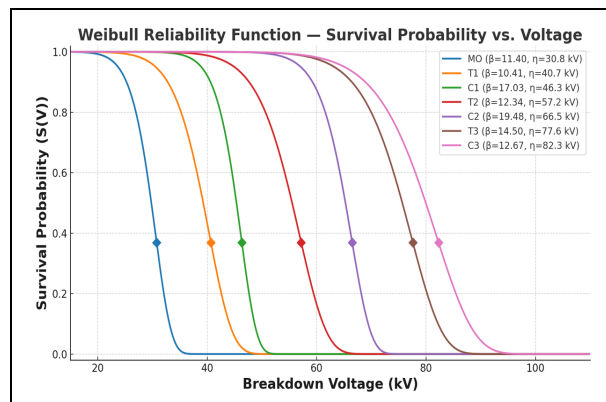


Fig. 9: Weibull reliability curves of BDV

The variation in BDV may be due to moisture, adsorbed gases, thermal stability, and dispersion homogeneity. Minor anomalies during these procedures may increase the voltage dispersion as per IEC 60156 circumstances. Hence, the moisture removal and uniform nanofiller dispersion is ensured during the test procedure. Compared to untreated TiO₂ nanofillers, mineral oil with CQD-treated insulating TiO₂

nanofillers shows better breakdown strength. This might be because TiO₂ nanofillers have a relaxation time constant that allows free electrons to be quickly captured on the surface of the nanoparticles. Additionally, CQD provides surface protection for inorganic materials and is less than 5 nm. Reports indicate that partial CQD coating on the surface of nanoparticles does not change the hydrophilic properties of the insulating nanoparticles. Therefore, it could lead to moisture from the oil medium being absorbed, which would improve the breakdown strength.

The breakdown voltage characteristics of the tested insulating oil samples were analysed using a two-parameter Weibull distribution, as shown in Fig. 8. Each dataset contained 20 breakdown voltage values, which were fitted to estimate the shape parameter (β) and scale parameter (η). These parameters represent the dispersion and characteristic strength of the insulation system, respectively.

Table 3. Shape and scale parameters of BDV

Sample	β (Shape)	η (Scale, kV)
MO	11.4	30.77
T1	10.41	40.69
C1	17.03	46.34
T2	12.34	57.2
C2	19.48	66.51
T3	14.5	77.6
C3	12.67	82.3

The results in Table 3 show that the base oil (MO) has the lowest η value of 30.77 kV. This implies reduced dielectric strength and a higher probability of failure at lower voltages. In contrast, the treated and composite nanofluid samples (T1–C3) show higher η values, reaching up to 82.3 kV, which indicates improved dielectric endurance. The β values range from 10.41 to 19.48, suggesting that nanofluid samples have consistent and reliable insulation behaviour with less variation compared to the base oil. C3 nanofillers would have led to lower effective surface area, reduction in charge-trapping and lower values compared to C2 due to reduced agglomeration.

When the loading is low, the nanoparticles are dispersed and uniformly scavenge electrons, providing uniform breakdown behaviour. With a higher concentration of nanofillers, agglomeration, particle chaining, and field distortion will happen, which leads to the formation of high-stress areas in a localised way and uneven charge transfer. These impacts bring more variability in breakdown events, which distribute the statistical distribution tightly and decrease β . Therefore, although the BDV is on average high, a reduction in the breakdown strength with an increase in filler levels means that the reliability of the process is reduced at higher levels of filler, therefore lowering the expected value of β . These findings confirm that adding TiO₂ and CQD nanofillers greatly improves the dielectric stability and breakdown reliability of the insulating medium.

The Weibull reliability curves in Fig. 9 show the survival probability $S(V) = 1 - F(V)$ for each insulating sample as a function of applied voltage. The characteristic scale parameters η increase from MO (30.77 kV) to C3 (82.30 kV), indicating improved dielectric strength for treated or composite samples. Higher shape parameters β (for example, C2: 19.48) indicate a narrower spread in failure distribution and therefore more consistent breakdown behaviour. The plotted diamond markers represent η (where $S(V) = 0.368$), providing a clear visual reference for characteristic strength across samples.

3.3 Tan Delta, Dielectric Constant and Volume Resistivity

Fig. 10 shows how the nano filler content affects the nanofluid's dielectric loss factor ($\tan \delta$). Samples that used CQD particles without nano-filler show a much higher $\tan \delta$ value as the temperature gradient increases. The graph compares the loss factor ($\tan \delta$) of different nanofluid samples made from mineral oil (MO), TiO_2 (T1, T2, T3), and CQD- TiO_2 (C1, C2, C3) at various temperatures (50°C, 70°C, 90°C, and 110°C). It shows that pure mineral oil has the highest loss factor at all temperatures, indicating more dielectric losses. TiO_2 nanoparticles (T1, T2, T3) lower the loss factor compared to MO, and higher concentrations (T3) further decrease the loss factor. CQD- TiO_2 nanofluids (C1, C2, C3) consistently have lower loss factor values than TiO_2 variants at every temperature and show better dielectric characteristics with reduced energy losses.

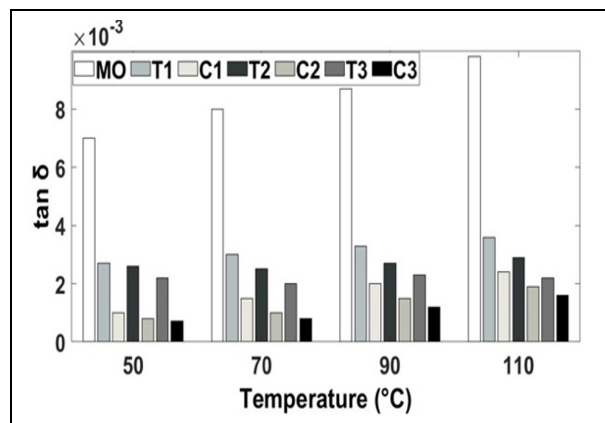


Fig. 10: Dielectric loss factor versus temperature for test samples

The lowest loss factor occurs in the CQD- TiO_2 variant with the highest nanoparticle concentration (C3). This means it performs better in terms of insulation under thermal stress. CQD- TiO_2 nanofluids again demonstrate lower dielectric losses and better insulation stability as the temperature rises, compared to TiO_2 nanofluids and pure mineral oil. CQD functionalization offers sufficient surface states which trap mobile charge carriers more effectively compared to bare TiO_2 and inhibits conduction loss. In larger doses, CQD- TiO_2 particles are well stabilised, creating a well-organised interfacial network inhibiting dipolar high-energy relaxation and restricting thermally activated charge emission. This is what stabilises the dielectric response over heat and reduces the dissipation of energy. This highlights their suitability for high-voltage and thermal applications. For the samples containing nano fillers treated with CQD, the dielectric

loss factor showed little change as the temperature increased. In comparison to similar samples (T1, T2, and T3) with uncoated TiO_2 particles, most of the samples with CQD- TiO_2 particles have dielectric loss factors that are nearly two orders of magnitude lower.

Fig. 11 shows that the dielectric constant of pure mineral oil, TiO_2 nanofluids (T1, T2, T3), and CQD- TiO_2 nanofluids (C1, C2, C3) changed with temperature at 50°C, 70°C, 90°C, and 110°C. CQD- TiO_2 nanofluids (C1, C2, C3) had the highest dielectric constant values at all temperatures, surpassing pure mineral oil. All samples showed an increase in the dielectric constant as the temperature rose; however, the CQD- TiO_2 samples improved the most. This suggests they have better polarisation behavior and energy storage potential. The highest concentration CQD - TiO_2 sample (C3) showed a relative increase in dielectric constant of about 8 to 10 % at each temperature point, showing a clear enhancement in dielectric properties and charge-holding ability. CQD- TiO_2 (C3) has a dielectric constant of about 2.1 at 50°C, while MO has a dielectric constant of approximately 1.9, showing an increase of nearly 10%. At all temperatures, CQD- TiO_2 nanofluids consistently exhibit a higher dielectric constant compared to the base oil by 8-10%.

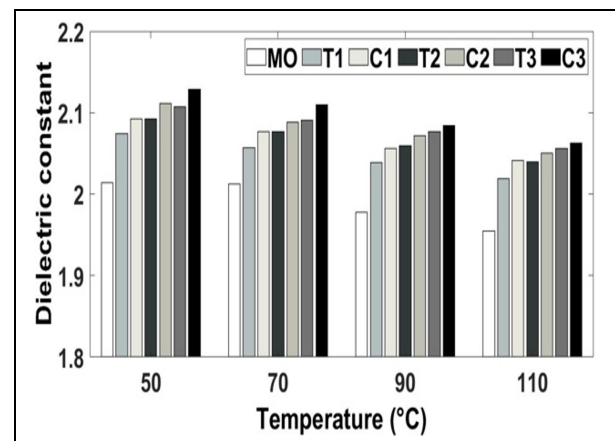


Fig. 11: Dielectric constant versus temperature for test samples

These dielectric liquids likely have two main sources of dielectric loss. In high electric fields and temperature ranges, charge carriers gathered at the interface cannot maintain interfacial polarisation loss. This loss is caused by increases in temperature and the applied electric field. The second source of loss is conduction loss, which occurs due to leakage current from imperfections, pores, and closely spaced conducting particles in the liquid dielectrics, as they are not perfect insulators (Wang *et al.* 2023). Even when TiO_2 particles are added, dielectric loss increases. The uncoated particles in the TiO_2 test sample touch each other and create many conductive paths. However, the dielectric loss factor of TiO_2 samples with coated CQD particles does not change much as the filler dosage increases. The insulating core-shell structure of the QD particles explains this. The CQD shell tightly surrounds the core of the TiO_2 particle, preventing direct contact and limiting the movement of free charge carriers. Wang also reported similar findings when studying a practical method to use core-shell particles to improve the dielectric properties of carbon black/epoxy composites.

Fig. 12 shows the change in volume resistivity ($\Omega \cdot \text{cm}$) versus temperature ($^{\circ}\text{C}$) at low temperatures for the samples marked MO, T1, T2, T3, C1, C2, and C3. The temperature range is between 50°C and 110°C , and the resistivity values fall within $10^{13} \Omega \cdot \text{cm}$. The data indicate that the volume resistivity steadily decreases as temperature increases for all the samples. This behaviour reflects the typical thermally activated conduction characteristics of insulating or dielectric materials. In this data set, the CQD-modified compositions (C1-C3) display higher resistivity values than the unmodified or TiO_2 -based samples (MO, T1-T3). This suggests that the addition of carbon quantum dots improves insulation properties. Sample C3 has the highest resistivity by a significant margin, indicating that it offers better charge-trapping and interface polarisation effects, leading to greater stability in electrical insulation at high temperatures.

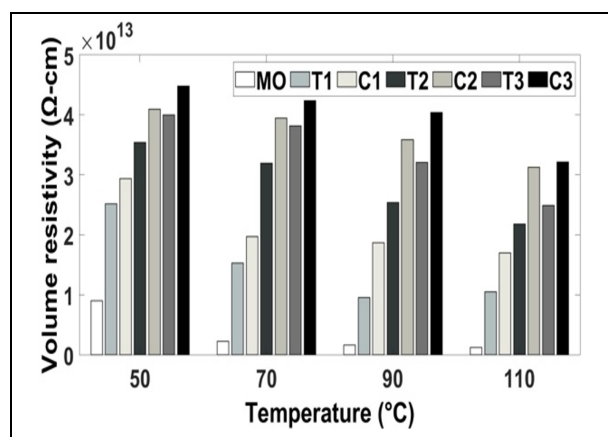


Fig. 12: volume resistivity constant versus temperature for test samples

3.4 Viscosity, Flash Point and Fire Point

Fig. 13 that the viscosity of the nanofluid sample changes little with the addition of TiO_2 nanoparticles, and it nearly reaches a constant value at higher concentrations. In contrast, the viscosity of the CQD sample increases slightly but not much high deviation were found between nanofluids and MO sample, even with surface treatment the nanoparticles altered the viscosity with very slight margin. When we compare the viscosities of a specific nanofluid sample at a certain concentration, the viscosity at 75°C is much lower than at 30°C . This is because the distance between the liquid molecules increases. CQD treatment possibly makes viscosity higher since the functionalised TiO_2 nanomaterials get into stronger contact with the ester molecules within FR3 oil (Lv *et al.* 2025), thus forming a thicker interfacial coating and a more structured nanoparticle ecosystem. This results in more resistance to flow and causes a significant elevation in viscosity.

Fig. 14 shows a bar graph that compares the flash point and fire point temperatures ($^{\circ}\text{C}$) of the starting material, MO, and several modified oil samples: T1, C1, T2, C2, T3, and C3. In each case, the flash point temperatures were lower than the fire point temperatures. This is expected because the flash point is the lowest temperature at which the vapour pressure of a substance can creates an ignitable flash, and the fire point is the lowest temperature at which it can sustain combustion for at least five seconds. The flash point of MO is at the lowest level of 150°C . Typically, the modified samples show an increase in

the flash point. C1 and C3 have the highest flash point at about 158°C . A similar pattern is observed for the fire point, with MO showing the lowest temperature, around 160°C . The fire point consistently rises in the modified samples, with C2 and C3 showing the largest increase to around 166°C . CQD-treated oils exhibit higher flash and fire points since CQD-modified nanoparticles increase intermolecular stability, slow evaporation of volatile molecules in the oil and form stronger intermolecular interactions within the oil. This makes formation of vapor slow and ignition is delayed leading to larger flash/fire temperatures. This suggests that the modification process mainly aims to improve the thermal stability and reduce the volatility of the original MO material.

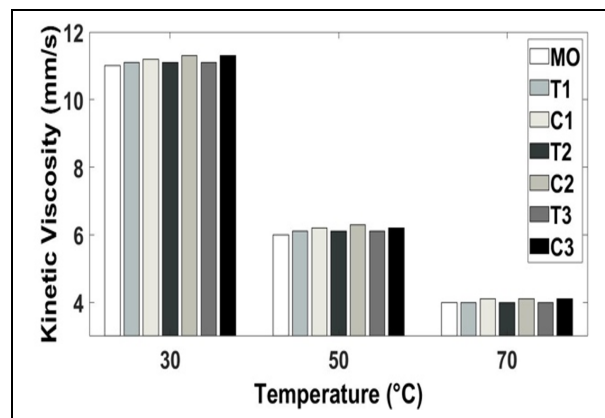


Fig. 13: viscosity versus temperature for test samples

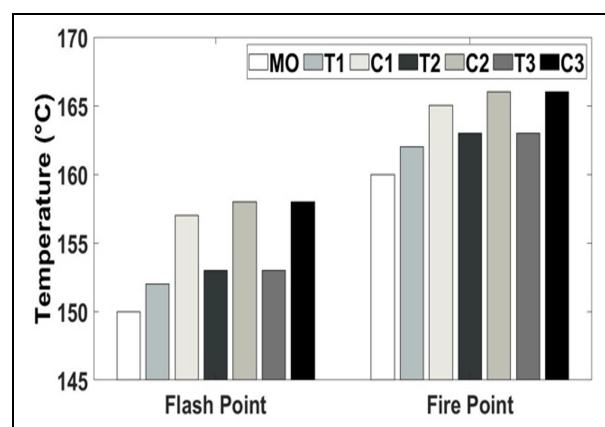


Fig. 14: Flash point and fire point for test samples

4. CONCLUSION

The study demonstrates that the integration of carbon quantum dots modified TiO_2 nanoparticles into dielectric liquids is an effective direction for the development of dielectric materials in the future. The surface modification by CQD shows great synergy with the dispersion of nanoparticles at interfaces, polarisation and the relaxation of charges. This is the reason why there is a significant increase in the relative permittivity, low loss factor and retained capacitance of the dielectric material. Additionally, the high-volume resistivity of the nanofluid produced ensures that it will have a high level of insulation resistance when subjected to high voltage. Additionally, the thermal characteristics of the nanofluid developed, including its high flash point and fire point, along

with the optimal viscosity, enhance the stability and safety of the nanofluid when used under severe environmental conditions. In this study, the narrow range of concentrations of nanoparticles was taken into account because the situations were reduced to the laboratory conditions and studied during the short periods of time. The present investigation was not conducted on long-term ageing, ingress of moisture or that of transformer material compatibility. Future works should concern the long-term reliability of a wider range of concentrations, other surface functionalization, and hybrid fillers. In-depth investigation of the underlying mechanisms combined with field-level validation and advanced modelling would also make these materials applicable to high voltage and smart-grid insulation about to be implemented.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

- Abdi, S., Harid, N., Boubaker A., Haddad, M. and Boubakeur, A., Comprehensive assessment of transformer oil after thermal aging: modeling for simultaneous evaluation of electrical and chemical characteristics, *Energies*, 18(8), 1915 (2025). <https://doi.org/10.3390/en18081915>
- Bibi, S., Shakir, N., Sadiq, M., Sadiq, S., Ullah, I., Khan, Q., Bostan, B. and Ismail, M., Investigating the structural, dielectric, optical and photocatalytic properties of carbon dots and palladium, platinum decorated carbon dots, *Mol. Struct.*, 138488(2024). <https://doi.org/10.1016/j.molstruc.2024.138488>
- Bojovschì, A., Quoc, T. V., Trung, H. N., Quang, D. T. and Le, T. C., Environmental effects on HV dielectric materials and related sensing technologies, *Appl. Sci.*, 9(5), 856 (2019). <https://doi.org/10.3390/app9050856>
- Chandrasekar, S. and Montanari, G. C., Analysis of partial discharge characteristics of natural esters as dielectric fluid for electric power apparatus applications, *IEEE Trans. Dielectr. Electr. Insul.*, 21(3), 1251–1259 (2014). <https://doi.org/10.1109/TDEI.2014.6832272>
- Danial, A. R., Walvekar, M., Khalid, M., Vaka, and Mubarak, N. M., Recent progress and challenges in transformer oil nanofluid development: a review on thermal and electrical properties, *IEEE Access*, 7, 151422–151438 (2019). <https://doi.org/10.1109/ACCESS.2019.2946633>
- Djurovic, D., Karaman, D., Vasic, D. and Pejanovic, D., Dielectric relaxation response of electrical insulating liquids under different natures of thermal stress, *J. Mater. Res. Technol.*, 25, 1599–1611 (2023). <https://doi.org/10.1016/j.jmrt.2023.06.033>
- Dsouza, S. D., Buerkle, M., Brunet, P., Maddi, C., Padmanaban, D. B., Morelli, A., Payam, A. F., Maguire, P., Mariotti, D. and Svrcek, V., The importance of surface states in N-doped carbon quantum dots, *Carbon*, 183, 1–11 (2021). <https://doi.org/10.1016/j.carbon.2021.06.088>
- Fofana, I., Bouaïcha, A., Farzaneh, M., Sabau, J., Bussi eres, D. and Robertson, E. B., Decay products in the liquid insulation of power transformers, *IET Electr. Power Appl.*, 4(3), 177–184 (2010). <https://doi.org/10.1049/iet-epa.2009.0181>
- Girish, K. M., R. Lavanya, M. V., Hemantha, R. G. R., Rajath, B. N., Deepak, K. and Prashantha, S. C., Dielectric and conductivity studies of Tb-doped zinc orthotitanate nanomaterials for next-generation electronics and energy storage, *Solid State Ionics*, 432, 117048(2025). <https://doi.org/10.1016/j.ssi.2025.117048>
- Haque, S. M., Ardila-Rey, J. A., Umar, Y., Mas’ud, A. A., Muhammad-Sukki, F., Jume, B. H. and Bani, N. A., Application and Suitability of Polymeric Materials as Insulators in Electrical Equipment, *Energies*, 14(10), 2758 (2021). <https://doi.org/10.3390/en14102758>
- Karataş, M. and Bicen, Y., Nanoparticles for next-generation transformer insulating fluids: A review, *Renew. Sustain. Energy Rev.*, 167, 112645 (2022). <https://doi.org/10.1016/j.rser.2022.112645>
- Koch, M., Tenbohlen, S. and Djamali, M., Influence of thermal aging on dielectric properties of natural ester oil-impregnated paper, *IEEE Trans. Dielectr. Electr. Insul.*, 17(3), 762–770 (2010). <https://doi.org/10.1109/TDEI.2010.5412009>

- Kong, J., Wei, Y., Zhou, F., Shi, L., Zhao, S., Wan, M. and Zhang, X., Carbon quantum dots: properties, preparation, and applications, *Mol.*, 29(9), 2002 (2024).
<https://doi.org/10.3390/molecules29092002>
- Küchler, A., High Voltage Engineering: Fundamentals – Technology – Applications, Springer Vieweg, 2018.
<https://doi.org/10.1007/978-3-642-11993-4>
- León, A., Reuquen, P., Garín, C., Segura, R., Vargas, P., Zapata, P. and Orihuela, P. A., FTIR and Raman Characterization of TiO₂ Nanoparticles Coated with Polyethylene Glycol as Carrier for 2-Methoxyestradiol, *Appl. Sci.*, 7(1), 49 (2017).
<https://doi.org/10.3390/app7010049>
- Li, Y., Wang, K., Hou, W. and Wang, L., Carbon quantum dots for environmental catalysis: green synthesis, surface functionalization, and interface engineering, *Chem. Commun.*, 61, 18784–18797 (2025).
<https://doi.org/10.1039/D5CC04350F>
- Lundgaard, L. E., Hansen, W., Linhjell, D. and Painter, T. J., Aging of oil-impregnated paper in power transformers: influence of moisture, oxygen and acidity on cellulose insulation, *IEEE Trans. Power Delivery*, 19(1), 121–131 (2004).
<https://doi.org/10.1109/TPWRD.2003.820175>
- Lv, Y., Li, C., Sun, Q., Huang, M., Cheng, L. and Qi, B., Effect of Dispersion Method on Stability and Dielectric Strength of Transformer Oil-Based TiO₂ Nanofluids, *Nanoscale Res. Lett.*, 11, 515 (2016).
<https://doi.org/10.1186/s11671-016-1738-5>
- Lyutikova, M., Korobeynikov, S. and Kononov, A., Evaluation of the properties of mixtures of aromatic mineral oil and synthetic ester for high-voltage equipment, *IEEE Trans. Dielectr. Electr. Insul.*, 28(4), 1282–1290 (2021).
<https://doi.org/10.1109/TDEI.2021.009636>
- Mansour, D. E. A., Shaalan, E. M., Ward, S. A., El Dein, A. Z., Karaman, H. S. and Ahmed, H. M., Multiple nanoparticles for improvement of thermal and dielectric properties of oil nanofluids, *IET Sci. Meas. Technol.*, 13(7), 968–974 (2019).
<https://doi.org/10.1049/iet-smt.2018.5015>
- Palanisamy, K. V., Subramaniam, C. and Sakthivel, B., Evaluating the role of carbon quantum dots covered silica nanofillers on the partial discharge performance of transformer insulation, *Turk. J. Electr. Eng. Comput. Sci.*, 30(4), 1492–1505 (2022).
<https://doi.org/10.55730/1300-0632.3861>
- Palanisamy, K. V., Subramaniam, C. and Sakthivel, B., Investigations on novel carbon quantum dots covered nanofluid insulation for medium voltage applications, *J. Electr. Eng. Technol.*, 15(1), 269–278 (2020).
<https://doi.org/10.1007/s42835-019-00316-5>
- Parekh, K., Upadhyay, R., Rajňák, M., Dolník, B., Timko, M. and Kopčanský, P., Effects of static electric field and temperature on the dynamic dielectric responses of mixed oil-based and bilayer-stabilised magnetic fluids, *Nanoscale*, 17, 22927–22939 (2025).
<https://doi.org/10.1039/D5NR02856F>
- Rafiq, M., Shafique, M., Ateeq, M., Zink, M. and Targitay, D., Natural esters as sustainable alternating dielectric liquids for transformer insulation system: analyzing the state of the art, *Clean Technol. Environ. Policy*, 25(4), 31 (2023).
<https://doi.org/10.1007/s10098-023-02688-9>
- Saini, S. and Harid, N., Correlation between dielectric dissipation factor and resistivity in aged transformer oils, *Energies*, 16(1), 381 (2023).
<https://doi.org/10.3390/en16010381>
- Salah, M. E., El-Sharkawy, R., Ibrahim, M. A. and Abdel-Galil, A. M., The role of the accumulated surface charge on nanoparticles in improving the breakdown strength of liquid and solid insulation, *Energies*, 15(13), 4860 (2022).
<https://doi.org/10.3390/en15134860>
- Stone, G. C., Partial discharge diagnostics and electrical equipment insulation condition assessment, *IEEE Trans. Diele. Electric. Insul.*, 12(5), 891–904 (2005).
<https://doi.org/10.1109/tdei.2005.1522184>
- Suhaimi, S. N., Rahman, A. R. A., Md. Din, M. F., Hassan, M. Z., Ishak, M. T. and Jusoh, M. T. B., A Review on Oil-Based Nanofluid as Next-Generation Insulation for Transformer Application, *J. Nanomater.*, 1–17 (2020),
<https://doi.org/10.1155/2020/2061343>
- Szcześniak, D. and Przybyłek, P., Oxidation stability of natural ester modified by means of fullerene nanoparticles, *Energies*, 14(2), 490 (2021).
<https://doi.org/10.3390/en14020490>
- Viswanathan, P. K., Chandrasekar, S. and Sakthivel, B., Influence of CQD modified silica nano fillers on PD characteristics of transformer oil, *IEEE 4th Int. Conf. Condition Assess. Tech. Electri. Syst.*, 1–5 (2019).
<https://doi.org/10.1109/CATCON47128.2019.CN0051>

- Viswanathan, P. K., Chandrasekar, S. and Sakthivel, B., Influence of carbon quantum dots modified silica nanoparticles on insulation properties of mineral oil, *Proc. Int. Conf. High Vol. Eng. Appl.*, 10(2019). <https://doi.org/10.1109/ICHVET.2019.8724259>
- Wang, B., Wu, H., Hou, W., Fang, Z., Liu, H., Huang, F., Li, S. and Zhang, H., Optimizing dielectric polarization for electromagnetic wave attenuation via an enhanced Maxwell–Wagner–Sillars effect in hollow carbon microspheres, *J. Mater. Chem. A*, 11(43), 23498–23510 (2023). <https://doi.org/10.1039/D3TA05647C>
- Wu, Y., Chen, R., Zhang, J. and Tang, C., The influence of doping with different surface-modified SiO₂ nanoparticles on the dielectric properties of natural ester insulating oil, *Renew. Energy*, 228, 120671 (2024). <https://doi.org/10.1016/j.renene.2024.120671>
- Xia, G., Wu, G., Gao, B., Yin, H. and Yang, F., A New Method for Evaluating Moisture Content and Aging Degree of Transformer Oil-Paper Insulation Based on Frequency Domain Spectroscopy, *Energies*, 10(8), 1195 (2017). <https://doi.org/10.3390/en10081195>
- Xue, Q., Timoshkin, I., Given, M. J., Wilson, M. P. and MacGregor, S. J., Mobility of charge carriers in dielectric liquids (mineral oil, synthetic and natural esters), *High Vol.*, 6(6), 1040–1050 (2021). <https://doi.org/10.1049/hve2.12098>
- Yoon, H., Chen, G. and Hosier, I., Influence of thermal ageing on dielectric properties of natural ester oil-impregnated paper, *IEEE Trans. Dielectr. Electr. Insul.*, 30(3), 1337–1344 (2023). <https://doi.org/10.1109/TDEI.2023.3268039>
- Zhang, Z., Zuo, F., Cai, T., Gai, X., Wan, L., Lin, H., Wang, B. and Zhang, H., Modification of insulating oils and oil-based titanium dioxide nanofluids for transformers: a review, *Phys. Chem. Chem. Phys.*, 25, 22565–22582 (2023). <https://doi.org/10.1039/D3CP02135A>