

Plant-Mediated ZnO Nanoparticles as Functional Additives for Enhancing the Dielectric and Optical Response of Nematic Liquid Crystal

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Abstract

The present work investigates the influence of green-synthesized ZnO nanoparticles (NPs) derived from *Caesulia axillaris* Roxb. leaf extract, on the optical and dielectric parameters of a thermotropic nematic liquid crystal (NLC), namely 4'-heptyl-4-biphenylcarbonitrile (7CB). Synthesised NPs were characterised by UV-Visible spectroscopy analysis, which confirmed a band gap of 3.13 eV, while X-ray diffraction (XRD) observed an average crystallite size of ~ 5.41 nm. Moreover, FESEM and HRTEM investigations provided detailed insights into the structural morphology. To investigate their effect on NLC behaviour, 0.5 wt.% of ZnO NPs were dispersed in 7CB (4'-Heptyl-4-biphenylcarbonitrile) NLC and optical and dielectric properties were examined for the resulting LC nanocomposite.

Temperature controlled polarised optical microscopic study demonstrated an increase in isotropic temperature (T_{N-I}) of 0.5 wt% ZnO NPs-7CB composite by 3.9% indicating enhanced molecular interactions between 7CB molecules and ZnO NPs resulting in improved orientational ordering. Dielectric spectroscopy results revealed a substantial enhancement in dielectric permittivity value by $\sim 67\%$, as compared to pristine 7CB. The LC nanocomposite also showed reduction in dielectric loss, suggesting lower dielectric energy dissipation and better molecular polarization. Further, zeta potential and photoluminescence measurements revealed improved stability and modified electronic interactions in the LC nanocomposite system. Overall results demonstrate enhanced dielectric anisotropy, improved molecular ordering, and increased stability of the nanocomposite highlighting its potential for applications in advanced liquid crystal displays, photonic devices, and electro-optical technologies.

1. Introduction

Liquid crystals (LCs) are a special and very interesting phase of matter that blends with the traits of conventional liquids and crystalline solids. In this phase, the molecules exhibit long-range orientational order but still flow like a fluid. Based on their molecular arrangements, they are classified into various phases, but the most widely studied phase is Nematic. In NLCs, the rod-like molecules align parallel to each other along a common axis, well known as the director ($\mathbf{n}$), but they do not have positional order like in solid crystals [1], [2], [3], [4], [5]. Due to their molecular arrangement and elongated shape, NLCs exhibit anisotropic optical properties. Since their refractive index changes with polarization and the direction of incident light relative to the $\mathbf{n}$, make NLCs easy to manipulate light very precisely. These properties make NLCs highly sensitive towards external factors such as electric fields, magnetic fields and temperature [6], [7], [8] making them highly useful in various photonics, advanced displays, thermal sensors, and electro-optical device applications[9]. Further, their optical, dielectric and electro-optic properties can be altered using different metal and non-metal oxide nanostructures such as TiO_2 , MgO , CuO , ZnO , etc. [10], [11], [12], [13] [14], [15], [16], [17], [18], [19] Among these, ZnO nanoparticles (ZnO NPs) are particularly chosen due to their biocompatible, environmentally safe nature and ease of synthesis through physical, chemical, and green approaches. ZnO NPs have outstanding properties due to a large bandgap of 3.37eV with a larger excitation binding energy of 60 MeV at ambient room temperature,

making them a suitable candidate for applications in optical, electro-optical, sensing and photochemical areas [20], [21].

Previous research on dispersion of ZnO NPs have demonstrated significant effect of dispersing these NPs on the optical, dielectric and electro-optic response of NLCs [22], [23], [24], [25]. Early work by Manohar et al. (2009) investigated chemically synthesized ZnO NPs dispersed 5CB NLC and reported notable modifications in Freedericksz transition voltage, switching response time, and rotational viscosity of 5CB, highlighting the role of ZnO NPs in improving electro-optical performance [26]. Further, Khusboo et al. (2016), observed enhancement in thermo-acoustic properties such as sound velocity and molar volume by dispersing ZnO into 8CB LC in SmA as well as N phase, indicating altered intermolecular interactions within the liquid crystalline matrix [27]. Pandey et al. (2018), examined 5CB dispersed with chemical synthesized ZnO NPs under UV radiation and reported significant modifications in dielectric response attributed to enhanced charge separation and stabilization of molecular dipoles under UV light exposure[28]. While, another study by Pushpavathi et al. (2019) reported shift in photoluminescence (PL) spectral peak along with modification in I-V characteristics indicating improved charge transport mechanisms [29]. Jayaprada et. al, reported 80 CB doped with ZnO NPs which further improved PL intensity and dielectric properties, with optimum doping levels contributing to better optical performance and thermal stability [30]. Recently, Jangid et al. reported green-synthesized ZnO NPs into nematic liquid crystal (LCPD-40300) and observed the modification in dielectric anisotropy, conductivity, and electro-optical response of the latter [31]. Collectively, the available literature confirms the significant role of ZnO NPs in tuning physical properties of NLC materials. However, studies exploring the impact of green-synthesized ZnO NPs on the dielectric and electro-optical properties of 5CB NLC remain limited, thereby motivating the present investigation.

In the present work, ZnO NPs were successfully synthesised by green synthesis route using *Caesulia axillaris* Roxb. leaves extract, which is a cost-effective and eco-friendly route. These NPs were further characterized using UV-Visible spectroscopy, XRD, FESEM and HRTEM techniques and then dispersed into 7CB NLC at a concentration of 0.5 wt.%. The optical and dielectric properties of 0.5 wt.% ZnO NPs-7CB nanocomposite were thoroughly investigated over a range of temperatures and frequencies. The results provide valuable insights into the interaction between green-synthesized ZnO NPs and NLC molecules.

2. Experimental details

2.1 Materials

The NLC material used here is 7CB (4'-Heptyl-4-biphenylcarbonitrile), a member of 4-n-alkyl-4-cyanobiphenyl homologous series. It exhibits crystalline to nematic phase transition at 30.5°C and nematic to isotropic phase transition at 42.8°C along with positive dielectric anisotropy. Planar aligned cells with an active area of 25 mm² and thickness ~ 5 µm procured from Instec, USA were used in the present study. The incorporation of ZnO NPs into the 7CB NLC well influences the LC-molecular

arrangement through interfacial interactions, leading to enhanced molecular ordering as illustrated in Fig. 1.

Several characterization tools were used to evaluate the optical, structural and morphology of the prepared ZnO NPs. UV-visible spectroscopy was performed using an Agilent Cary 60 UV-Vis. spectrophotometer. The instrument is equipped with xenon flash lamp functioning in 190–1100 nm with a spectral bandwidth of 1.5 nm. Fourier-transform infrared (FTIR) spectroscopy was performed in the range of 400–4000 cm^{-1} using a Bruker Tensor 27 instrument at 4 cm^{-1} resolution. X-Ray diffraction analysis (PANalytical X'Pert PRO), equipped with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) was used to study the crystalline structure and phase purity of ZnO NPs. Surface morphology with elemental composition of NPs were investigated using FESEM (Zeiss Sigma 300), coupled with an Oxford Instruments energy-dispersive X-ray (EDX) spectroscopy system for elemental mapping. Detailed microstructural traits were investigated using HRTEM (JEOL JEM-2100F), which was operated at 200 kV.

The textural and morphological features of pure 7CB, NLC and 0.5 wt% ZnO NPs-7CB composite were studied using polarised optical microscopy (POM) (LV100POL, Nikon Eclipse, Japan) coupled with a Q-imaging camera (CCD) at 10x magnification under the crossed polarizer and analyser configurations. The scanning rate of heating and cooling cycles and the digital storage of data were controlled by Linksys software (Q28378) at a scanning rate of 0.1°C.

The dielectric properties of pure and nanocomposite were evaluated over the frequency range of 4 Hz-10 MHz, with the help of an Impedance Analyser (Wayne Kerr, 6500B).

The photoluminescence (PL) spectroscopy on pure and nanocomposite samples was performed using a Cary Eclipse Agilent Technologies fluorescence spectrophotometer. Further, the colloidal stability and surface charge characteristics of the ZnO NPs were measured using Malvern Instruments Limited zeta potential analyzer at room temperature.

2.2 Synthesis of ZnO NPs:

Fresh leaves of *Caesulia axillaris* Roxb. plant was brought by local source and used as the natural source of phytochemicals for the green synthesis of ZnO NPs. The collected leaves were first cleaned with double-distilled water to eliminate dust particles and other impurities present on surface followed by shade-dried at normal temperature conditions. Dried leaves were cut into small pieces and 250 g of these leaves were boiled in 2 L of distilled water for 6.5 hrs at 60°C to extract the bioactive compounds. The obtained plant extract was filtered out by using Whatman filter paper to remove solid residue and stored at 4°C for further use.

Zinc acetate dihydrate $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$, with a molecular weight of 219.50 g mol^{-1} and purity of 99.5%, was used as the zinc precursor for the synthesis of ZnO NPs. Ammonium hydroxide (NH_4OH) was used for pH regulation during the chemical process. For the reaction, zinc acetate solution was mixed with the prepared extract under continuous stirring condition while the pH was maintained pH at

9.5 using NH_4OH . The reaction mixture was then heated in a Teflon-lined autoclave at 160°C for 17 h. The resulting precipitate was centrifuged and washed with distilled water and ethanol repeatedly to remove residual impurities and unreacted species. The resulting sample was further dried at 80°C and ground to obtain well-crystalline pure ZnO nanopowder.

2.3 Preparation of and filling of planar LC cells

LC-nanocomposite was prepared by adding 0.5% wt. green synthesised ZnO NPs into pure 7CB NLC. The mixture was sonicated in glass vials at 33 kHz frequency to ensure uniform dispersion. To further enhance the distribution of NPs within the LC matrix, the mixture was heated above the isotropic transition temperature of 7CB, NLC and then allowed to cool slowly at room temperature to ensure uniform and stable nanocomposite system[32]. To investigate optical and dielectric properties, both pure 7CB and ZnO NPs doped 7CB samples were filled in empty planar aligned LC cells by capillary action at isotropic phase. The filled cells were then cooled down slowly at room temperature and sealed. Electrical connections were made for further characterizations [33], [34].

3. Results and discussions

3.1 Characterisation of synthesised ZnO NPs

3.1.1 UV-Visible spectroscopy

The optical absorption properties green-synthesised ZnO NPs were investigated using UV-Visible spectroscopy and the spectra is shown in Fig. 2(a). In the spectra, a strong absorption band is observed in the ultraviolet region with a maximum absorption at 356 nm, which can be due to the electronic transition from the valence band to the conduction band. The sharp absorption edge in the near-UV region confirms the formation of optically active ZnO NPs with good crystallinity and semiconducting nature [35].

The optical band-gap energy of the synthesized ZnO NPs was calculated using the well-known Tauc relation, $(\alpha h\nu)^n = A(h\nu - E_g)$, where α is the optical absorption coefficient, $h\nu$ is the photon energy, A is the material-dependent proportionality constant, E_g is the optical band gap energy, and n is the transition exponent. ZnO NPs shows a direct band gap semiconductor, and the band gap energy (E_g) was found to be ~ 3.13 eV. (Shown In Fig. 2 (b)) confirming the semiconducting nature of the ZnO NPs. The UV-Vis analysis revealed that the synthesized ZnO NPs possess a direct band-gap semiconducting nature. The optical band-gap energy (E_g), determined using the Tauc plot, was estimated to be approximately 3.13 eV (Fig. 2(b)). This value confirms the semiconducting behavior of the synthesized ZnO NPs and is in good agreement with the characteristic band-gap of ZnO. The obtained value of E_g for ZnO NPs is slightly less than the bulk ZnO which may be attributed to defect-mediated energy states, surface hydroxyl groups, oxygen vacancies, and residual organic molecules

from *Caesulia axillaris* Roxb. plant leaves extract. These surface and defect states can introduce localised energy levels within the band structure, leading to contraction of the optical band gap.

3.1.2 X-ray diffraction analysis

The crystalline phase, crystallite domain size, and structural purity of the prepared ZnO NPs were explored using the X-ray diffraction technique. Figure 3(a) shows the XRD spectrum of ZnO NPs, which displays discrete diffraction peaks at 32.07°, 34.27°, 36.32°, 47.63°, 56.81°, 59.44°, 62.83°, and 68.17°, corresponds to the miller indices (100), (002), (101), (102), (110), (103), (200), and (112) crystallographic planes, respectively. Peaks were perfectly matched with the standard JCPDS card no. 00-036-1451, which confirms the formation of a hexagonal wurtzite structure of ZnO NPs.

The absence of any secondary or additional diffraction peaks confirms the high phase purity of ZnO NPs within the detection limit of XRD technique. The interplanar spacing (d) for each observed diffraction plane was calculated using Bragg’s law ($n\lambda = 2d\sin\theta$). The calculated crystallographic parameters are well depicted in Table 1.

Table 1
Crystallographic parameters of green-synthesized ZnO NPs calculated from XRD data.

2theta (Degree)	Theta (Radians)	FWHM (Degree)	Plane	Interplanar Spacing (d)	Crystallite Size (nm)
32.07074	0.279870003	1.57641	(100)	0.279838543	5.243498924
34.27399	0.299096987	1.56878	(002)	0.262338563	5.29926339
36.32047	0.316955894	1.67747	(101)	0.248014334	4.984142622
47.63334	0.415679308	1.42154	(102)	0.191425958	6.10871343
56.81104	0.49576985	1.31152	(110)	0.162494314	6.886420546
59.43684	0.518684277	1.83678	(103)	0.155929172	4.980144912
62.82711	0.548269965	1.83479	(200)	0.148308302	5.073434188
68.17073	0.594901846	2.02877	(112)	0.137930428	4.728083675
Average size =					5.412962711

The average crystallite size of synthesized ZnO NPs calculated using the Debye-Scherrer equation; $D = K\lambda / \beta \cos\theta$, where K is the shape factor, λ is the X-ray wavelength (1.5406 Å for Cu radiation), β is the full width at half maximum (FWHM) of the diffraction peak, and θ is the Bragg angle. The average crystallite size was found to be ~ 5.41 nm. Overall, the XRD results confirm that the green synthesis approach has successfully synthesised phase-pure, nanocrystalline hexagonal wurtzite ZnO NPs. The nanoscale crystallite size and well-defined crystal structure of NPs are expected to provide

abundant surface-active sites, which may enhance the functional performance of LC when dispersed in optimum concentration.

3.1.3 FESEM and HRTEM analysis:

The surface morphology, elemental composition, and microstructural features of the green synthesised ZnO NPs were explored using FESEM coupled with EDS and HRTEM equipped with SAED, as shown in Fig. 4. The FESEM micrographs shown in Fig. 4(a) disclose the formation of compact and quasi-spherical agglomerated ZnO NPs with a coarse and highly textured surface morphology. The surface is composed of closely packed granular nanostructures, indicating that the synthesized material is not a smooth bulk phase but an assembly of nanoscale ZnO domains. In the present study, the aggregation may also be influenced by phytochemical residues from *Caesulia axillaris* Roxb., which can act as capping and stabilizing agents during nucleation and growth during reaction. The FESEM image in Fig. 4(b) further proves that the agglomerated particles are composed of small nanosized grains. The elemental composition of the NPs was studied by EDS analysis, which confirmed the presence of Zinc and Oxygen as the major elements, with atomic percentages of 53.40% and 46.60%, respectively, representing the successful formation of ZnO NPs with high compositional purity.

The HRTEM images shown in Fig. 4 (c, d) show the morphology and crystalline nature of the prepared ZnO NPs. The particles appear as quasi-spherical nanocrystalline domains, consistent with the FESEM results. Well resolved lattice fringes are visible in the HRTEM image proving high crystalline nature of NPs. The overlay of individual grains further supports the tendency of ZnO NPs to group due to their great surface activity and probable biomolecule-mediated surface interactions. The corresponding SAED pattern shown in Fig. 4 (c) demonstrates well-defined concentric diffraction rings and supporting the polycrystalline nature of the synthesized ZnO NPs. Observed diffraction rings are indexed to the (100), (002), (101), (102), (103), and (110) planes of hexagonal wurtzite ZnO NPs. These indexed planes are in good agreement with the XRD results further validating the precise formation of ZnO NPs. The continuous concentric diffraction rings indicate numerous randomly oriented nanocrystals instead of a single-crystal domain. Overall, FESEM reveals rough and agglomerated nanoparticle assemblies. EDS verifies Zn and O as the dominant elemental constituents. HRTEM confirms nanoscale crystalline domains with visible lattice fringes, the histogram analysis establishes an average particle size of 6.69 nm, and SAED validates the polycrystalline hexagonal wurtzite structure, crystalline ZnO NPs which may be suitable for dispersing them in LC matrix for modified optical and dielectric properties.

3.2 Characterization of LC nanocomposites

3.2.1 Surface morphology

Textural studies of pure 7CB, NLC and 0.5 wt% ZnO NPs-7CB composite were carried out using polarised optical microscope (POM) under cross polarisers position at a high resolution to evaluate the surface morphology of samples [36]. Textures were observed over the temperature range spanning the nematic to isotropic phases (34°C to 43°C) at the rate of 1°C. Textures were recorded during cooling cycle [37].

Figure 5 shows POM images of pure 7CB and 0.5 wt% ZnO-7CB composite at different temperatures. POM images reveal typical nematic texture of the samples. With increase in temperature, change in the textural color is observed because, as the temperatures increases, the molecular ordering and birefringence also changes. In 0.5 wt% ZnO NPs-LC composite, observation of fine dark dots distributed throughout the sample image confirms the incorporation of ZnO NPs within LC matrix without causing any significant disruption in the mesophase.

Comparison of phase transition temperature (measured from temperature dependent POM textures), revealed that T_{N-I} of ZnO NP-7CB composite (41.4°C) is higher than that of pure 7CB LC (39.9°C) which is calculated as 3.87%. This increase in the transition temperature of 7 CB with ZnO NPs indicates that ZnO NPs supports orientational stability of LC molecules due to better intermolecular interactions. Hence the thermal stability of the nanocomposite increases.

3.2.2 Dielectric spectroscopy

Dielectric spectroscopy is very useful technique to study the molecular dynamics of LCs and possible interactions mechanism between NPs and LC molecules [26], [38], [39]. Dielectric properties of pure 7CB and 0.5 wt% ZnO NPs-7 CB composite were evaluated over a wide range of frequency (100 Hz-10⁴ kHz) during cooling cycle (at rate of 1°C). At first LC sample cells were calibrated using air and a standard volatile reference material to ensure accuracy in measurement and then dielectric spectroscopy was performed on pure 7CB and 0.5 wt% ZnO NPs-7 CB composite[14].

Frequency-dependent dielectric permittivity (ϵ') and dielectric loss (ϵ'') of planar aligned pure 7CB and 0.5 wt% ZnO NP-7CB composite measured at different temperatures are shown in Figure. 6. In Fig. 6, a significant enhancement in ϵ' was observed with the incorporation of ZnO NPs in 7CB, NLC matrix. For this composite, the ϵ' increases by ~ 68% compared to pristine 7CB at 1 kHz frequency. The increase in ϵ' in composite could be attributed to the fact that ZnO NPs already possess dipole moment [41]. When such NPs are incorporated in LC matrix, the large interfacial area between ZnO NPs and LC molecules leads to Maxwell-Wagner-Sillars interfacial polarization. Also, such NP surface encourages local alignment of nearby LC molecules through surface anchoring interactions. Therefore, overall polarization of ZnO-LC composite increases resulting into a higher ϵ' . Whereas, dielectric loss (ϵ'') in the nanocomposite was found to decreased which can be attributed to the fact that the surface of NPs act as trapping sites for the free charge carries [42], [43], [44] and which creates localized energy states at their interfaces, capturing free ions and reducing their mobility. This results in the suppression of ionic conductivity and lowering of energy dissipation. Additionally, the ZnO NPs help in screening the electric field variations, which further stabilizes the system by preventing excessive energy dissipation. The combined effect of increase in ϵ' and decrease in ϵ'' demonstrate that green synthesised ZnO NPs can effectively improve the dielectric performance of 7CB LC system.

The frequency dependence of AC conductivity (σ_{ac}) of pure 7CB and 0.5 wt% ZnONPs-7CB composite is shown in Fig. 7. Both samples demonstrate the characteristic frequency dependent conductivity

behaviour which is usually shown by NLCs. In the low-frequency region, conductivity remains almost constant due to combined effect of electrode polarization and restricted ionic mobility within the nematic phase [45], [46], [47]. As the applied frequency increases, σ_{ac} starts to increase indicating increases contribution of localised hopping conduction and interfacial polarization.

Compared to pristine 7CB, 0.5 wt% ZnO NPs-7CB composite shows higher σ_{ac} conductivity over the whole range of frequency investigated. This increase in the σ_{ac} values can be attributed to introduction of additional NP-LC interfaces, enhanced interfacial polarization and NPs induced modification of dielectric environment which leads to frequency assisted transport of localised charge carries. Hence, these NPs generate localised charge accumulation resulting into localized paths for charge transport via hopping between nearby localised states [48].

Figure 7. Variation of AC conductivity (σ_{ac}) with frequency of pure 7CB and 0.5 wt% ZnO NPs-7CB composite.

3.2.3 Zeta-potential analysis

Zeta potential investigation was done to analyse surface charge features and dispersion stability of both green synthesised ZnO NPs and 0.5 wt% ZnO NPs-7CB composite. Here, zeta potential demonstrates the electrostatic potential (eV) at the shear (slipping plane) of dispersed particles and indicates the colloidal stability. It generally arises from the development of an electrical double layer at the particle-medium (distilled water) interface and measure the magnitude of the electrostatic repulsive forces between suspended particles [49].

Figure 8 shows the zeta potential distribution of pure 7CB and 0.5 wt% ZnO NPs-7CB composite. Pure 7CB shows zeta potential value of -15.9 mV, indicating moderate dispersion stability with relatively weak electrostatic repulsion. Whereas, with ZnO NP dispersion in 7CB matrix, the absolute value of the zeta potential increased from 15.9 mV to 42.2 mV. This substantial increase in negative surface potentials indicates that ZnO NPs incorporation in 7CB matrix significantly enhanced the electrostatic stabilization. This enhance stability can further be attributed the charged surface of ZnO NPs which might have modified the interfacial charge distribution and enhanced electrostatic repulsive forces between the particles. Additionally, a distinct sharp and single peak confirms for uniform dispersion without agglomeration. Overall, the significant increase in zeta potential magnitude confirms that the ZnO doped composite system's dispersion stability is significantly enhanced by dispersion of ZnO NPs into 7CB matrix. This enhanced electrostatic stability is likely to assist better NP dispersion in host LC matrix, leading to better NP-LC interactions. These observations are in good agreement with the enhanced dielectric permittivity observed for 0.5 wt% ZnO NPs-7CB composite.

Figure 8. Zeta potential distributions of pure 7CB and 0.5 wt% ZnO NPs-7CB composite.

3.2.4 Photoluminescence studies:

Figure 9. Photoluminescence spectra of pure 7CB and 0.5 wt% ZnO NPs-7CB composite.

The photoluminescence (PL) spectra of pure 7CB and 0.5 wt% ZnO NPs-7CB composite were recorded over the wavelength range of 350–550 nm and are shown in Fig. 9. Both the samples exhibit a wide emission band centred at around 395 nm which is the characteristic emission behaviour of 7CB NLC. PL spectra of nanocomposite do not show any appreciable shift in the emission band indicating that ZnO NPs does not affect the electronic transitions and overall preserving the emission characteristics of host 7CB [50]. However, the dispersion of ZnO NPs results in the significant increase in the PL intensity by approximately ~ 60% as compared to pristine 7CB. The interfacial molecular interactions between 7CB and ZnO NPs are believed to be responsible for the increased emission. Furthermore, the combined effect of large surface area of ZnO NPs that promote carrier localisation result in enhanced radiative exciton recombination and an enhanced charge carrier that traps at the interface of 7CB and ZnO NPs results in rise in exciton recombination, would consequently results in enhancing the emission intensity without disturbing its intrinsic emission properties [51].

4. Conclusions

In this study, ZnO NPs were successfully synthesised via green method using *Caesulia axillaris* Roxb. leaf extract and characterized by UV-Visible spectroscopy, XRD, RESEM and HRTEM. Results confirmed the formation of highly crystalline ZnO NPs with optical band gap 3.13 eV and an average crystallite size of 5.41 nm. These NPs were subsequently incorporated into 7CB, NLC at a concentration of 0.5 wt%. The incorporation of ZnO NPs into pure 7CB significantly influenced thermal, dielectric and optical properties of the nanocomposite. Results showed an increase in the clearing temperature (T_{N-I}) of composite by 3.9% as compared to pure 7CB, NLC, indicating improved thermal stability of composite. Dielectric permittivity was enhanced by 67%, and AC conductivity by 90.36%, supporting the improved polarization and charge transport arising from NP-LC interactions, better LC molecules alignment and enhanced interfacial polarization. Substantial increase in the magnitude of surface potential measured via Zeta potential indicate enhanced dispersion stability of the nanocomposite. Moreover, 60% increase in PL emission intensity of 7CB with ZnO NPs without any significant shift in the emission wavelength points that ZnO NPs dispersion in 7CB matrix results in effective interfacial interactions while preserving the characteristic emission of 7CB host. Overall, the present work demonstrate that green synthesised ZnO NPs provide an eco-friendly approach for improved dielectric and optical response of 7CB, NLC, highlighting their potential applications in advance display and other electro-optical applications [52], [53], [54], [55].

Declarations

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Authors Contribution

Geetika Jangid: Writing original draft, Validation, Investigation, Formal analysis, Data curation; **Sanjeev Kumar:** Writing– review & editing, Methodology, Formal analysis; **Gautam Singh:** Review & editing, Visualization, Validation; **Praveen Malik:** Review & editing, Formal analysis; **Harsh Sharma:** Writing – review & editing; **Rishi Pal:** Writing – review & editing; **Jasvir Dalal:** Writing – review & editing; **Jasdeep Kaur:** Writing – review & editing; **Supreet:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization, Funding Acquisition. All authors discussed the results, reviewed successive drafts, and approved the final version.

Data availability

Data will be made available on request.

Declarations Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

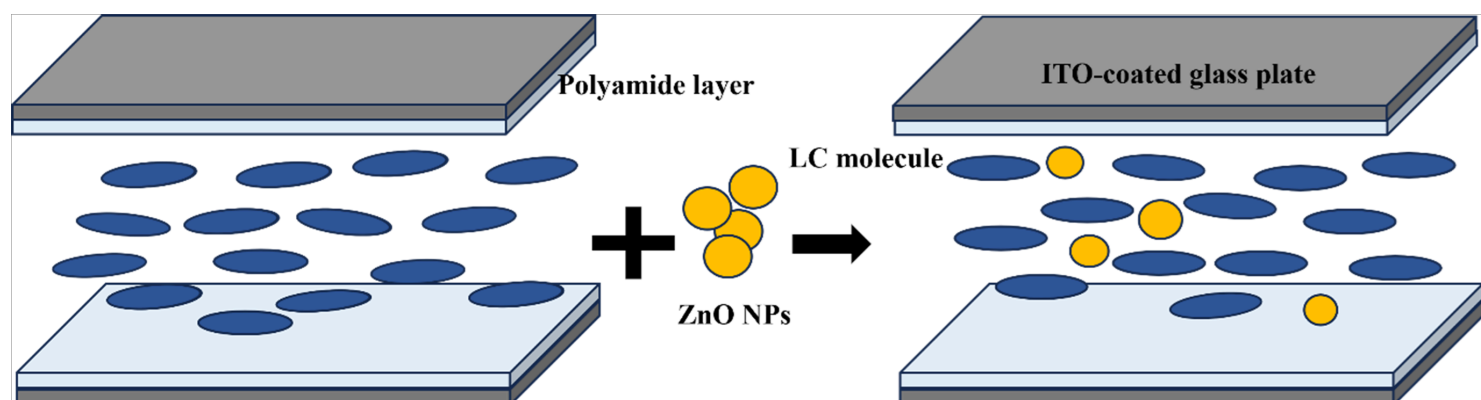


Figure 1

Schematic illustration of the molecular alignment of (a) pure 7CB liquid crystal molecules and (b) ZnO NPs dispersed 7CB nanocomposite.

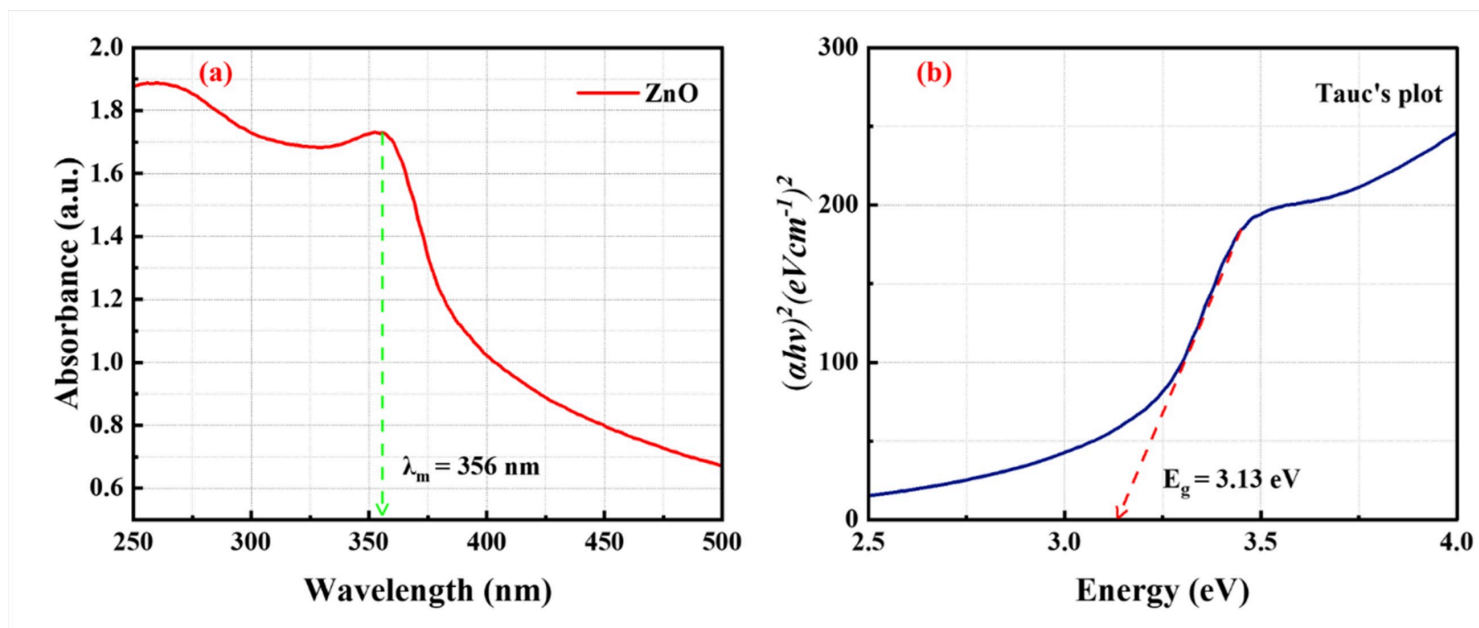


Figure 2

(a) UV-Visible absorption spectrum and (b) Tauc plot of $(ah\nu)^2$ versus photon energy of ZnO NPs.

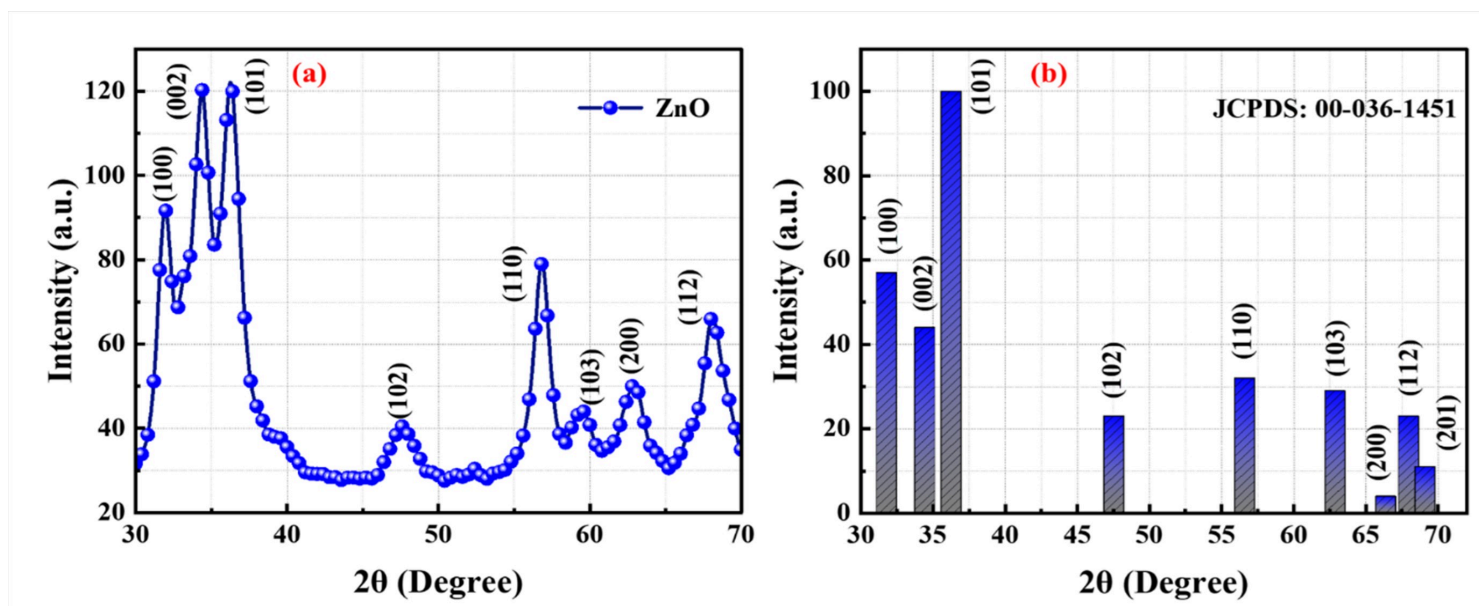


Figure 3

XRD analysis of green-synthesized ZnO NPs. (a) Experimental X-ray diffraction pattern of the synthesized ZnO NPs. (b) Standard reference diffraction pattern of ZnO matched with JCPDS card.

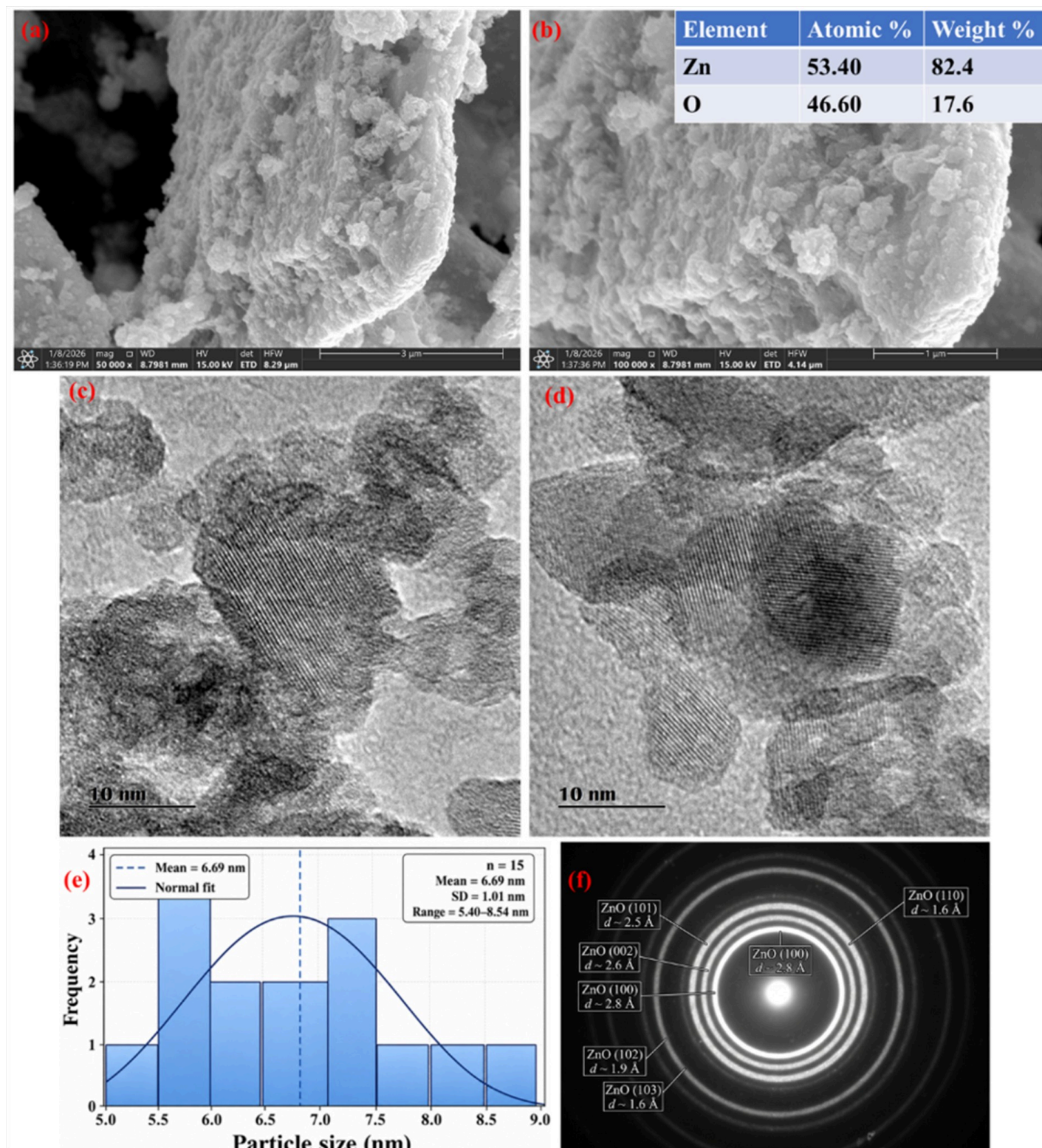


Figure 4

Morphological, elemental, and microstructural analysis of green-synthesized ZnO NPs. (a, b) FESEM micrographs showing agglomerated ZnO NP assemblies with rough, granular, and highly textured surface morphology. The inset in panel (b) shows the EDS elemental composition. (c, d) HRTEM images showing aggregated nanoscale ZnO (e) particle size distribution histogram for HRTEM analysis (f) SAED pattern of the prepared NPs.

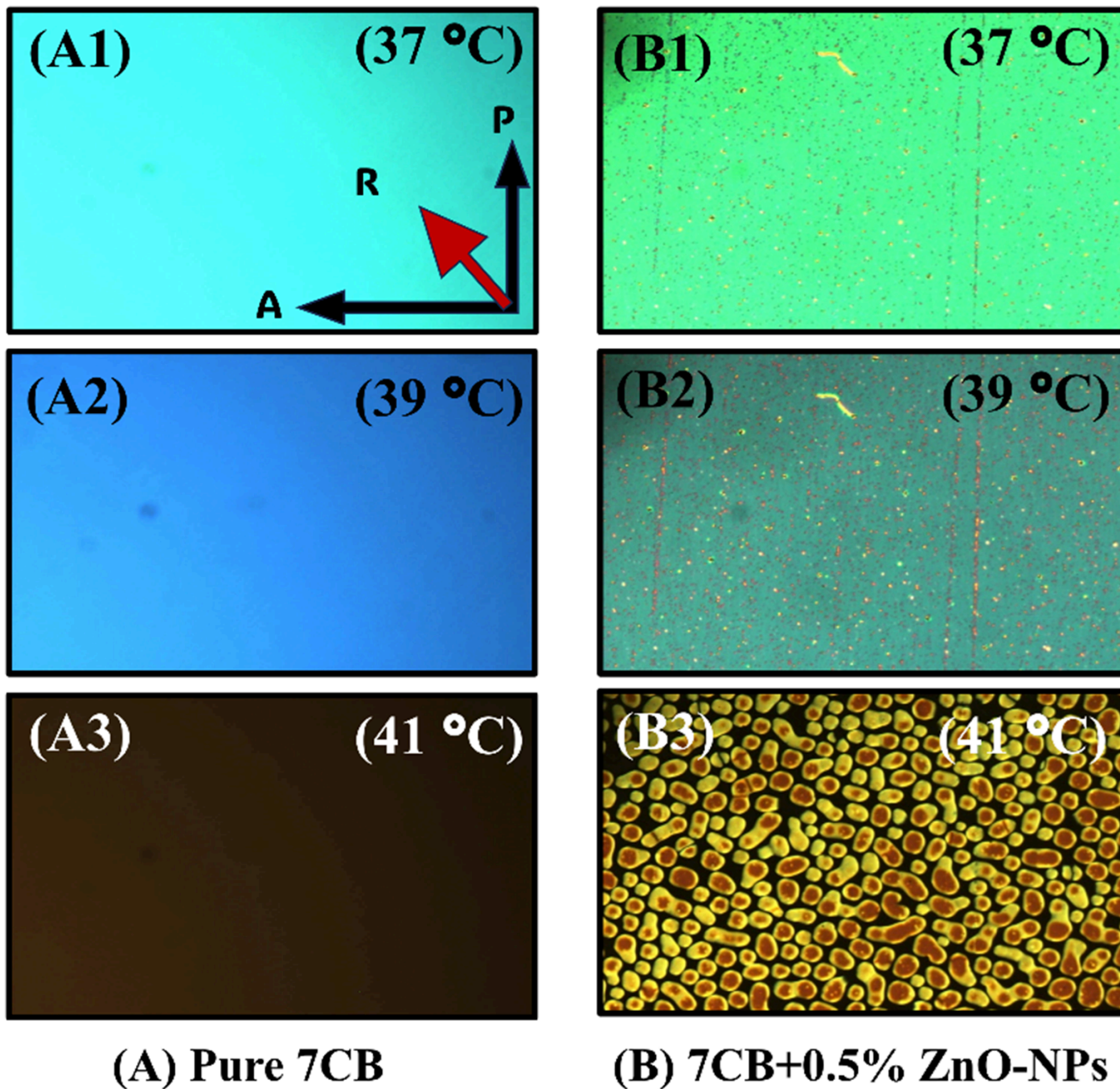


Figure 5

Textural images of (a) pure 7CB (b) 0.5 wt. % ZnO NPs-7CB composite at different temperatures (images were captured at 10X magnification, black arrows show the directions of cross-polarisers and red arrow shows the direction of rubbing of LC cells).

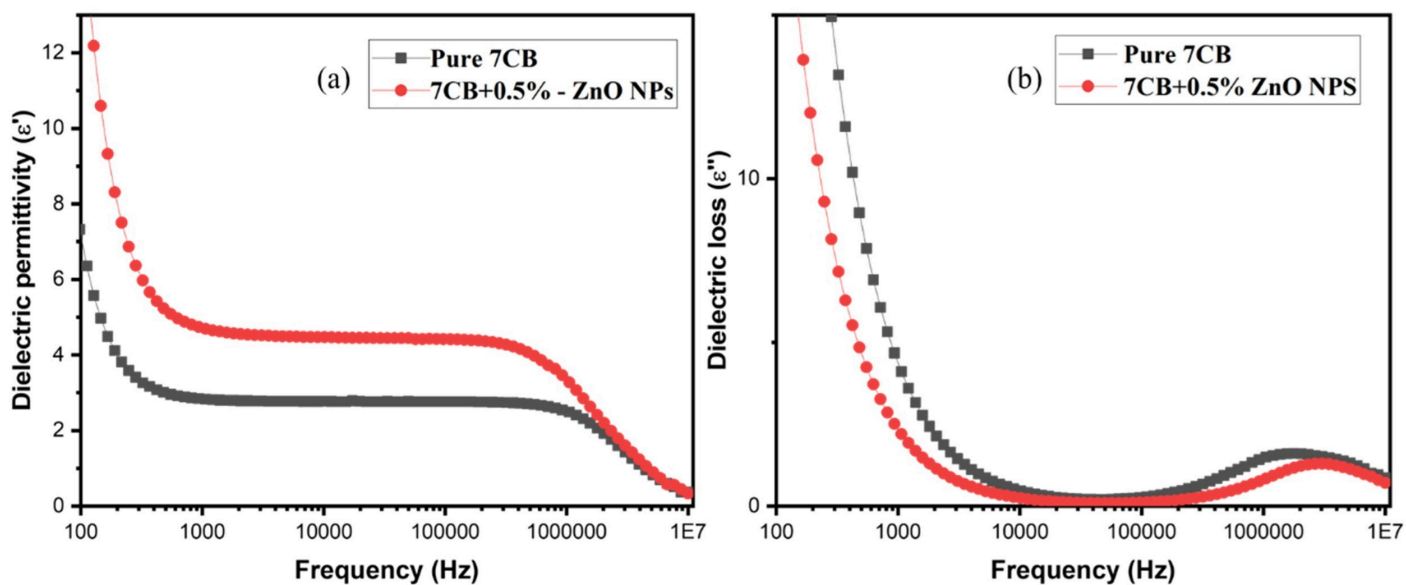


Figure 6

Frequency-dependent variation of (a) dielectric permittivity (ϵ') and (b) dielectric loss (ϵ'') spectra with frequency of planar aligned pure 7CB and 0.5 wt% ZnO NPs-7CB composite at 37°C.

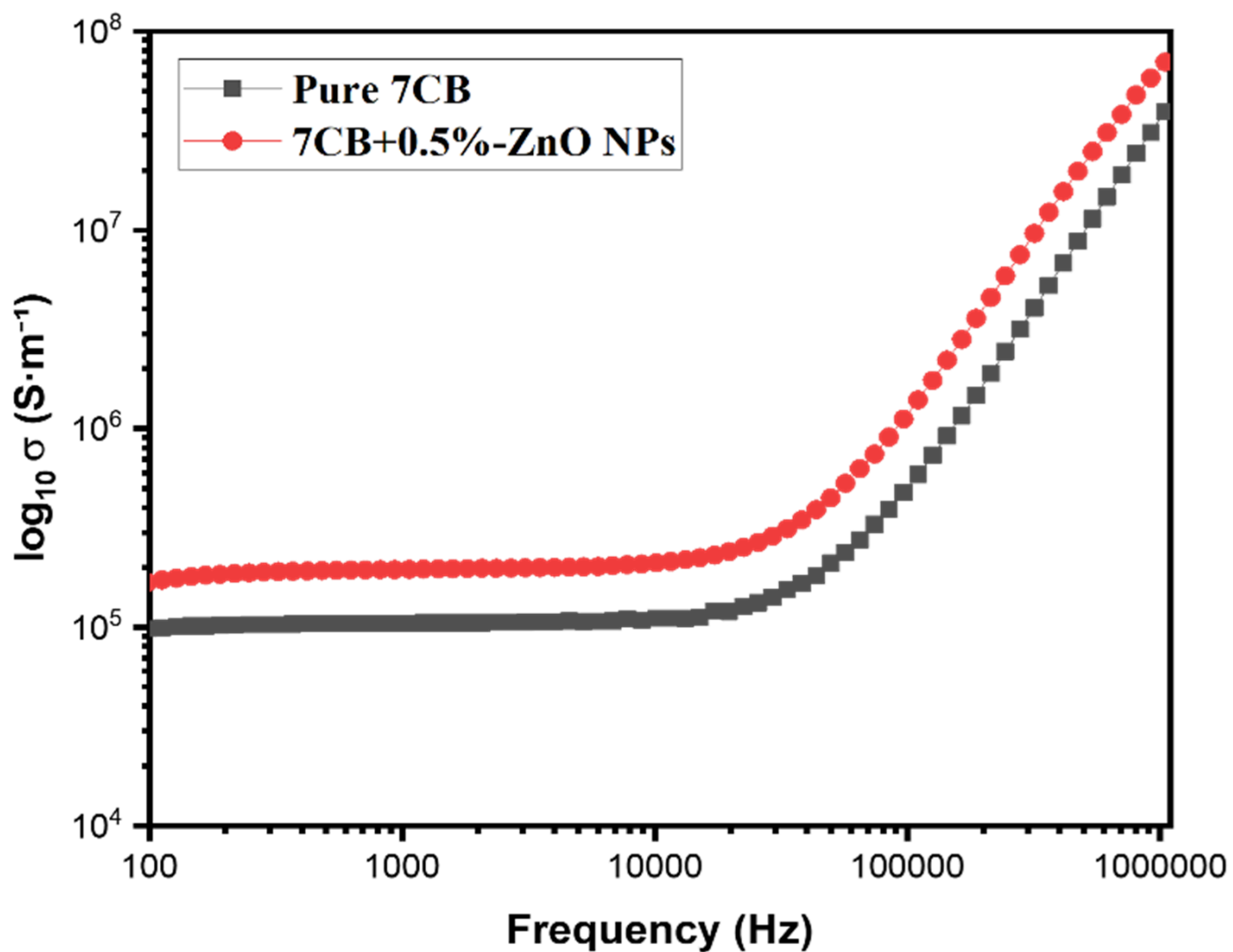


Figure 7

Variation of AC conductivity (σ_{ac}) with frequency of pure 7CB and 0.5 wt% ZnO NPs-7CB composite.

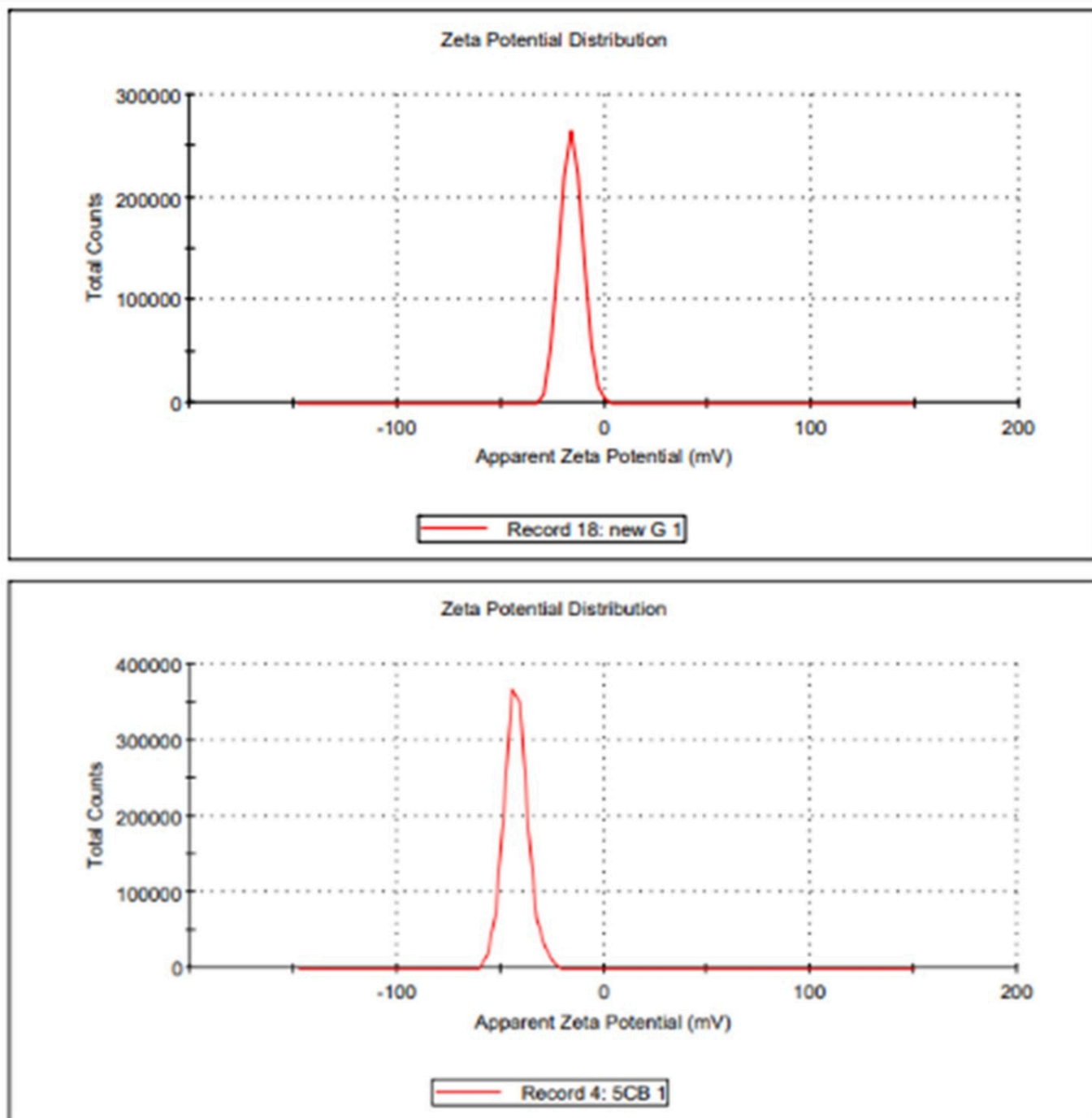


Figure 8

Zeta potential distributions of pure 7CB and 0.5 wt% ZnO NPs-7CB composite.

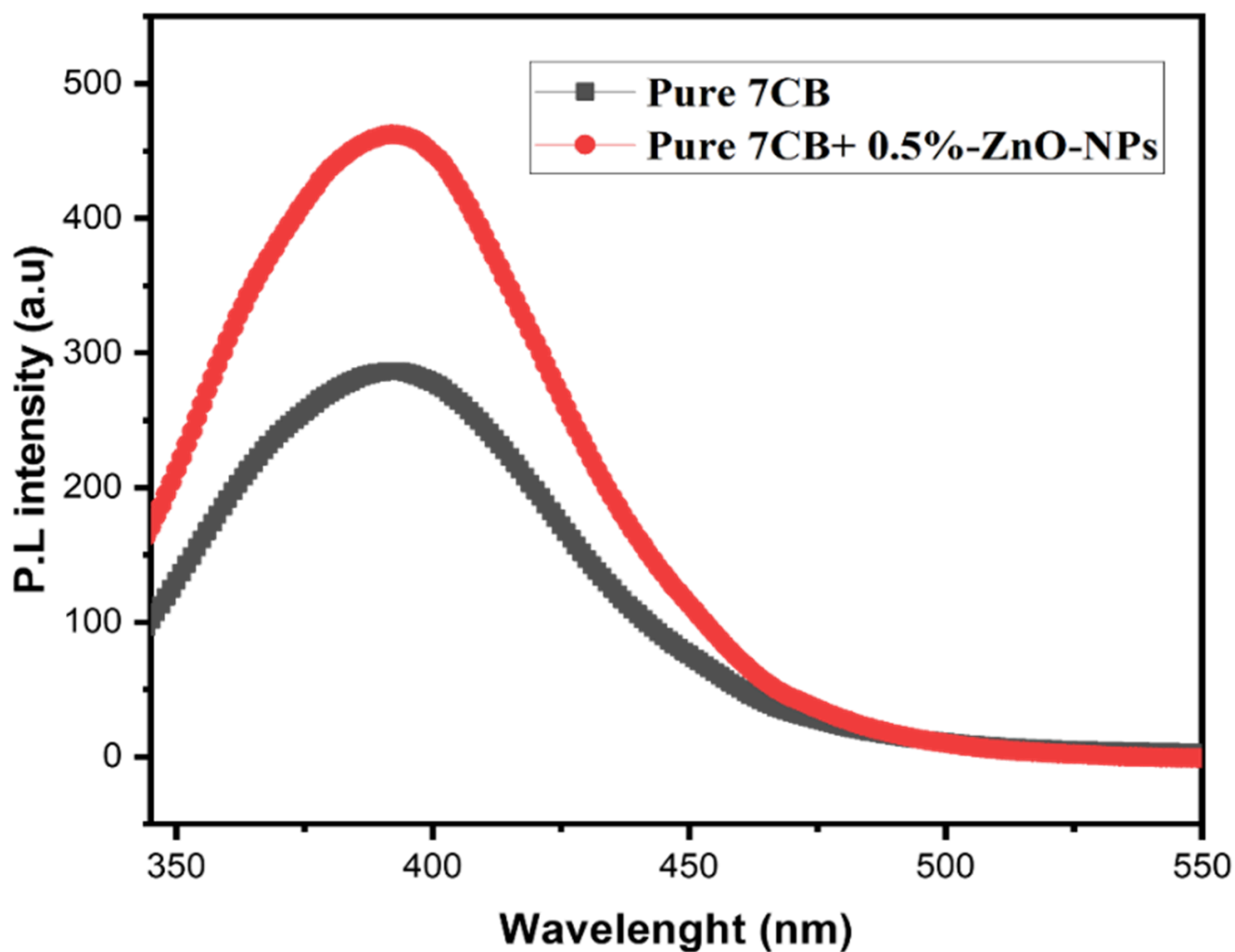


Figure 9

Photoluminescence spectra of pure 7CB and 0.5 wt% ZnO NPs-7CB composite.

Supplementary Files

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