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P. E. S. Bhaskar

Ramachandra College of Engineering (A)

B. V. Vamsi Krishna

Adikavi Nannaya University

R. K. Ramachandra

Government college (Autonomous)

G. Lalitha Devi

Sir. C. R. Reddy Degree College (A)

Z. Spandana

Government of Andhra Pradesh

N. Udaya Sri

D N R College(Autonomous)

M. V. S. Prasad

prasad2008mandru@gmail.com

D N R College(Autonomous)

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P. E. S. Bhaskar ^{a, b}, B. V. Vamsi Krishna ^a, R. K. Ramachandra ^c, G. Lalitha Devi ^d,

Z. Spandana ^e, N. Udaya Sri ^f, M. V. S. Prasad ^f, *

^a Department of Physics, Adikavi Nannaya University, Rajamahendravaram, Andhra Pradesh, 533296, India.

^b Department of Physics, Ramachandra College of Engineering (A), Eluru, Andhra Pradesh, 534007, India.

^c Research Advances in Materials (RAM) Science Centre, Govt. College (A), Rajamahendravaram, Andhra Pradesh, 533296, India.

^d Department of Electronics, Sir. C. R. Reddy Degree College (A), Eluru, Andhra Pradesh, 534007, India.

^e Ward Women Protection Secretary, Government of Andhra Pradesh, Gudivada, 521301, India

^f Department of Physics, D. N. R. College (A), Bhimavaram, Andhra Pradesh, 534202, India.

*Corresponding author's E-mail address: prasad2008mandru@gmail.com

ABSTRACT

Calcium Oxide nanoparticles (CaO NPs) were synthesised using Lemon Peel Powder Extract (LPE) (LPE-CaO NPs) through ultrasonic-assisted coprecipitation. The XRD pattern reveals the formation of crystalline LPE-CaO NPs with an FCC crystal structure, space group is $Fm\bar{3}m$, and the average crystallite size is 67.9977 nm. UV-Visible spectroscopy showed the maximum absorbance peaks at 264 nm for LPE, while the characteristic absorption at 300 nm in biosynthesised LPE-CaO NPs, indicates the CaO NPs formation. The photoluminescence (PL) study shows an intense emission peak centred at ~380 nm, which is consistent with the direct band gap (~3.181 eV) obtained from Tauc plot analysis. The FTIR peak at 522 cm^{-1} , attributed to the Ca-O stretching vibrations, supports the formation of CaO NPs, while FTIR peaks of LPE at 1224 cm^{-1} and 1026 cm^{-1} were attributed to the C-O and C-O-C stretching vibrations, acting as reducing and capping agents in the synthesis of CaO NPs. FESEM images show nearly spherical morphology, and the average particle size of LPE-CaO NPs is 87.88 ± 19.47 nm. Electrical impedance, electric modulus, and electrical conductivity have been examined at the frequency (f) (100 Hz-1 MHz) in the temperature range (303 K-383 K). The impedance decreases with increasing temperature, indicating a negative temperature coefficient of resistance (NTCR) in LPE-CaO NPs. The relaxation peaks in electric modulus analysis shift to higher frequencies with increasing temperature, indicating a decrease in relaxation time and confirming a thermally activated relaxation process. The activation energies obtained from electrical impedance ($E_{aZ} = 0.0741$ eV) and electric modulus ($E_{aM} = 0.073$ eV) are closely in agreement, supporting thermally activated relaxation behaviour in

LPE-CaO NPs. Therefore, these findings establish LPE-CaO NPs as a promising material for applications involving thermally activated electrical responses.

Keywords: CaO Nanoparticles, Lemon Peel Powder Extract, Ultrasonic-assisted Coprecipitation, Electrical Impedance, Electrical Modulus

1. Introduction

The growing demand for high-performance electronic devices such as capacitors, sensors, and energy storage devices has sped up extensive research on metal oxide nanoparticles (MONPs) due to their unique physicochemical properties[1]. The electrical behaviour of MONPs is highly sensitive to frequency and temperature, influenced by microstructural characteristics including grain size, grain boundaries, and defect states [2,3]. The charge transport, relaxation dynamics, and conduction mechanisms in nanomaterials are commonly studied by an LCR meter, providing complex impedance with a wide range of frequencies [4]. It is possible to distinguish grain and grain-boundary contributions and understand how charge carriers move in nanoscale systems by examining complex impedance (Z^*), electric modulus (M^*), and AC conductivity (σ_{ac}).

Calcium oxide (CaO) nanoparticles have a wide band gap of 7.1 eV [5], very stable at high temperatures [6], a high dielectric constant of 11.8, and are safe for the environment [7,8]. Impedance studies of CaO nanoparticles reveal that their electrical behaviour is highly frequency- and temperature-dependent, as evidenced by semicircular Nyquist plots that reflect contributions from both grain interiors and grain boundaries. Electric modulus analysis also helps us understand relaxation phenomena by getting rid of the effects of electrode polarisation, which makes bulk properties stand out. Previous work [9] demonstrates that the CaO NPs exhibit the frequency-dependent behaviour of AC conductivity due to thermal conduction of charge carriers.

The primary phytochemicals in Lemon peel are cellulose, hemicellulose, and pectin [10], acts as reducing and capping agents during the synthesis of MONPs. This makes the crystals more crystalline, less agglomerated, and more functional on the surface. These factors are very important for figuring out the electrical properties of nanoparticles because surface states and defects directly govern charge transportation and relaxation behaviour. The presence of residual biomolecules from lemon peel powder extract (LPE) on the nanoparticle surface can create localised energy states that make hopping conduction easier and change the impedance characteristics. It tends to improve the non-Debye relaxation behaviour, dielectric dispersion

and AC conductivity [11–13]. Thus, CaO nanoparticles made from Lemon Peel powder are a great way to study impedance-based electrical properties and electrical conductivity analysis.

In this context, the current study presents the biosynthesis of CaO nanoparticles utilising lemon peel powder extract, negative temperature coefficient of resistance (NTCR) of biosynthesised CaO NPs, phase purity, defect states, chemical compositions, frequency (100 Hz-1 MHz) and temperature (303 K-383 K) dependency behaviour of electrical properties such as electrical impedance, electric modulus formalism, and AC conductivity.

2. Experimental Methodology

2.1 Chemical and Materials

The analytical grades of Calcium Nitrate Tetrahydrate and Sodium Hydroxide were procured from SRL Chemical Pvt. Ltd, India. Lemon Peel powder was purchased from the local market, Anjaneya Herbals, NTR District, Andhra Pradesh, India.

2.2 Preparation of Lemon Peel Powder Extract (LPE)

10g of Lemon peel powder was dissolved in 100 ml of distilled water and kept in a hot air oven at 80 °C for 30 min. The extract of lemon peel was filtered through Whatman filter paper five times to remove undissolved particles. The resultant solution was stored safely in an airtight container, placed in a refrigerator at 4 °C for further studies.

2.3 Ultrasonic-assisted Coprecipitation of CaO Nanoparticles using LPE

Degas the LPE for 5 min under ultrasonication to get rid of air bubbles. 50 mL of LPE was added to 0.05 moles of $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ in 100 ml of distilled water during ultrasonication at 50 °C for 30 min. 0.1 moles of NaOH were added dropwise to the above mixture at 50 °C for another 30 min. The resultant mixture was stirred for 30 min at room temperature and left aside for 6 hours. The resultant solution was centrifuged for 3 times after each successive washed the precipitate with distilled water. Subsequently, the pellet was dried in a hot air oven at 100 °C for 4 h. The dried powder was calcinated at 600 °C for 3 h to obtain the crystalline nature of LPE-CaO NPs.

2.4 Preparation of LPE-CaO NPs Pellet

A 10 mm diameter high-density pellet was prepared in a uniaxial hydraulic press with an applied pressure of 6 tons. The thickness of the pellet (1.45 mm) was measured using a screw gauge. Then, the pellet was sintered at 150 °C for 2 h to remove air and increase strength. After

silver paste was applied to both sides of the pellets, it was dried at 40 °C for 6 h to ensure good contact between the silver electrode and the pellets.

2.5 Characterisation Techniques of LPE-CaO NPs

A D8 Advance X-ray diffractometer (Bruker, Germany) was utilised to determine the crystal structure of LPE-CaO NPs from the X-ray diffraction (XRD) pattern, recorded in the range 2θ (10° - 80° in degrees) with a step size of 0.02 Å, and Cu-K α wavelength is 1.5418 Å. The UV-Visible spectrophotometer (SHIMADZU, UV-2600 (230), Japan) was used to record the UV-Visible absorbance of LPE-CaO NPs as a function of wavelength range (200-800 nm) with a resolution of 0.5 nm. The Photoluminescence (PL) of LPE-CaO NPs was measured using an Agilent Cary Eclipse fluorescence spectrometer. The Fourier Transform Infrared spectroscopy (FTIR) spectra of LPE and LPE-CaO NPs were obtained using a Bruker instrument, using a KBR pellet in the wavenumber range 4000-400 cm $^{-1}$. The Field Emission Scanning Electron Microscopy (FESEM) images of LPE-CaO NPs were captured with diverse magnifications, and elemental compositions in LPE-CaO NPs were analysed through Energy Dispersion X-ray spectroscopy (EDAX) by CARL ZEISS NTS Ltd. The electrical impedance data were recorded with varying frequency (100 Hz- 1 MHz) in the temperature range (303 K- 383 K) by Wayne Kerr LCR meter, 4100 series.

3. Results and Discussions

3.1 Structural Analysis

XRD pattern of LPE-CaO NPs is depicted in Figure 1. The strong diffraction peaks at $2\theta = 32.19^\circ$, 37.35° , 53.82° , 64.11° and 67.36° are in good agreement with the cubic CaO (lime) phase and match well with the reference pattern (COD No. 96-900-6732). Match! Phase identification has assigned these reflections to cubic CaO phase with space group Fm-3m and lattice parameter $a=4.8130$ Å. The weak reflection at $2\theta \approx 42.88^\circ$ could not be indexed by the Match! search-match analysis and thus is not assigned to CaO in the present study. The XRD results thus confirm CaO as the main crystalline phase identified. A minor or poorly crystalline secondary contribution is, however, not totally ruled out based on the present XRD analysis alone. The XRD pattern of LPE-CaO NPs are well agreement with the literature report [14]. The 2θ angles, interplanar distance, and Full-Width Half Maximum (FWHM) values were presented in Table 1.

Table 1. The 2θ angles, interplanar distance, and FWHM values of LPE-CaO NPs

2θ (degrees)	d _{hkl} [Å]	FWHM (degrees)
32.19	2.7287	0.1079
37.35	2.4059	0.1099
53.82	1.7021	0.1343
64.11	1.4515	0.2353
67.37	1.3890	0.1611

The average crystallite size calculated using the Debye-Scherrer method, average dislocation density, and average micro-strain (ε) were determined by Williamson Smallman's relation and Stokes-Wilson's equation, respectively [15], and represented in Table 2:

$$D = \frac{k\lambda}{\beta \cos \theta} \quad (1)$$

Where D is the crystallite size at θ (radians), k is the shape factor constant (0.9), β is the FWHM in radians, λ is the wavelength of Cu- k_α radiation, and θ is the Bragg's diffraction angle in radians.

$$\delta = \frac{1}{D^2} \quad (2)$$

$$\varepsilon = \frac{\beta \cos \theta}{4} \quad (3)$$

Table 2. The average crystallite size, average dislocation density, and average micro-strain of LPE-CaO NPs

Sample	Debye-Scherrer		
	D (nm)	$\delta \times 10^{-3} \text{ (nm)}^{-2}$	$\varepsilon \times 10^{-3}$
LPE-CaO NPs	67.9977	0.21627	5.76855

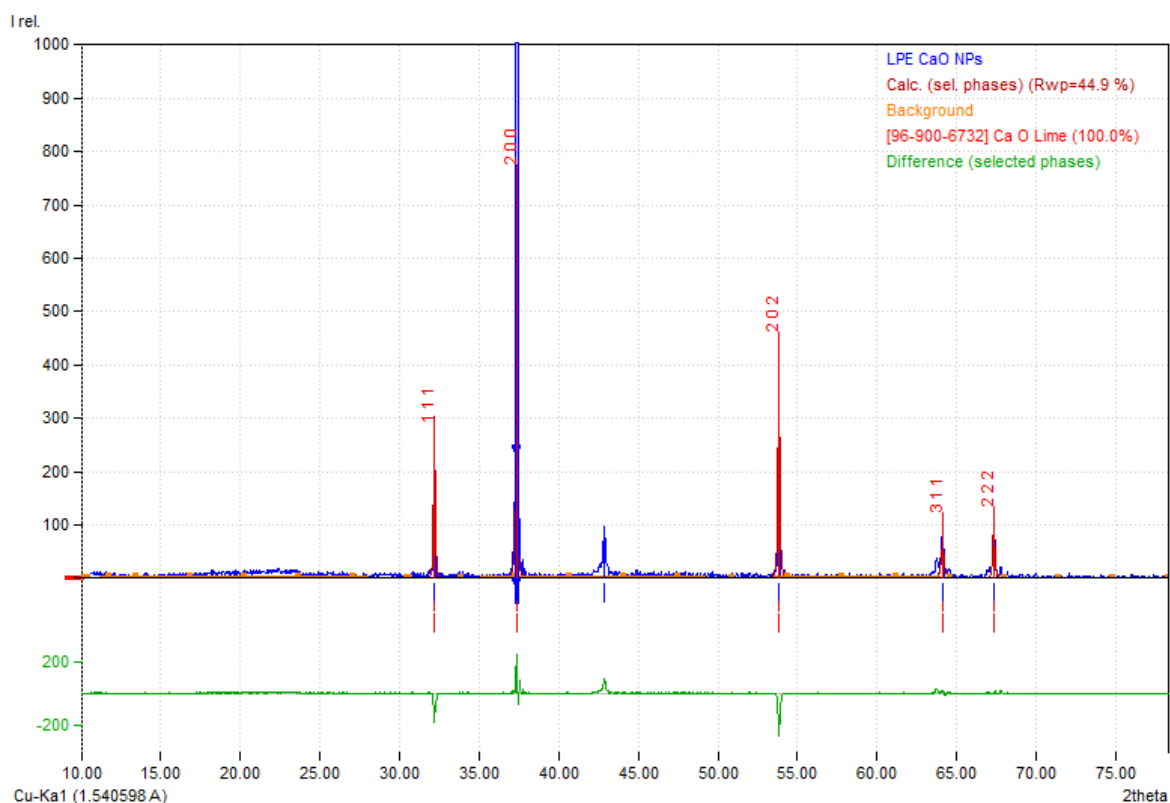


Fig. 1 X-ray diffraction pattern of LPE-CaO NPs

3.2 Optical Studies

3.2.1 Absorbance spectrum

The UV-Vis absorbance spectra of LPE-CaO NPs and LPE were recorded in the wavelength range of 200–800 nm (Fig. 2a, b, respectively). The LPE-CaO NPs exhibit a strong absorption band around ~212 nm that is ascribed to the electronic transitions involving the Ca-O lattice. A wider absorption feature is also observed around 300 nm, which may be related to surface states and/or residual phytochemical species associated with the biosynthesised nanoparticles. The LPE spectrum shows a maximum absorption at about 264 nm and a broad absorption region from about 224 nm to 305 nm, indicating the presence of phytochemical constituents in the lemon peel extract. This indicates that phytochemicals in LPE act as stabilising and capping agents during the formation of CaO NPs. This is in close agreement with the literature work [16].

3.2.2 Optical band gap

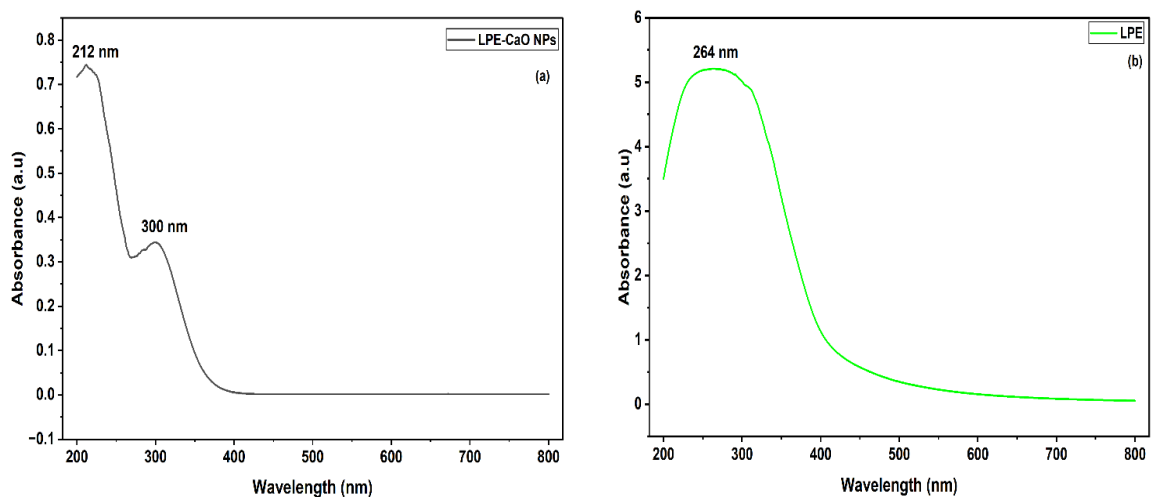
The direct energy band gap of LPE-CaO NPs was determined through Tauc plot equation (4) [17,18], Fig. 2c

$$(\alpha h\nu)^n = K (h\nu - E_g) \quad (4)$$

Where, ν is the frequency of incident UV-visible light, K is a proportionality constant, and n denotes the type of electronic transition ($n=2$ for direct transition). The direct band gap value was calculated by extrapolating a line to the curve on the energy axis. The estimated direct optical band gap was approximately 3.181 eV.

3.2.3 Photoluminescence (PL) Spectrum:

The PL spectrum of LPE-CaO NPs is depicted in Fig. 2d, recorded at room temperature with an excitation wavelength of 280 nm. The spectrum exhibits two emission features at ~360 nm and ~380 nm. The intense emission peak centred at ~380 nm corresponds to an emission energy of approximately 3.26 eV, which is attributed to near-band-edge (NBE) recombination of electron-hole pairs, which is in good agreement with the optical band gap (~3.181 eV) obtained from Tauc plot analysis (Fig. 2c). However, this PL emission is not regarded as a direct determination of the optical band gap. The observed emission could be attributed to radiative recombination of photoexcited carriers through band-edge and/or localised surface-related states. The weaker shoulder at about ~360 nm is attributed to defect-related or surface-state mediated emission. Defect-related states may arise from intrinsic structural imperfections as well as from surface states associated with the nanoparticle surface.



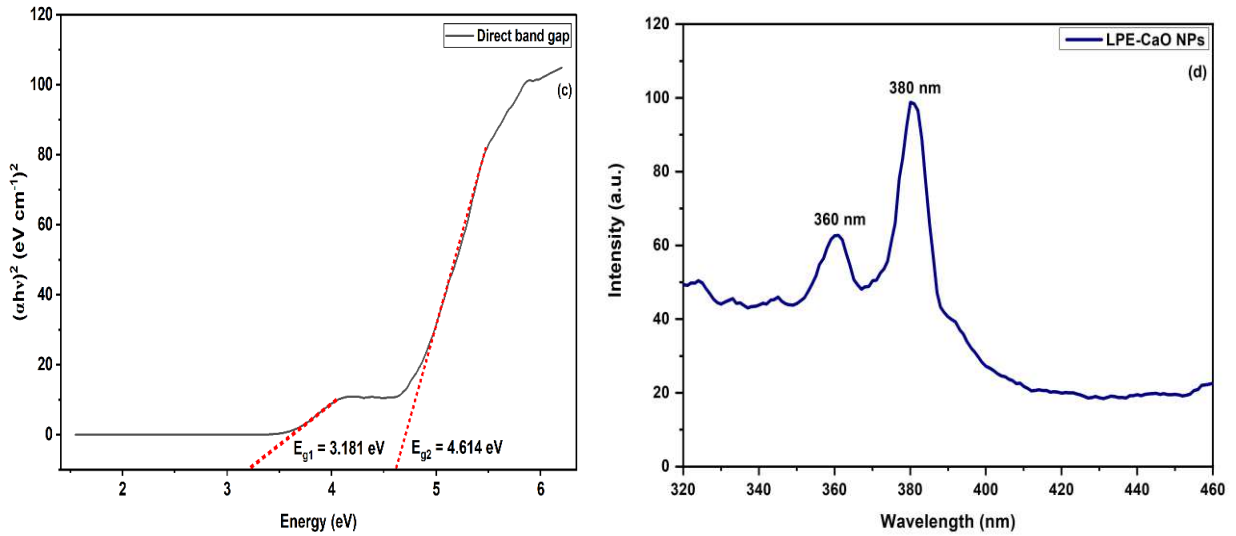


Fig. 2. Absorbance spectrum: a) LPE-CaO NPs, and b) LPE; c) Direct band gap spectrum of LPE-CaO NPs, and d) PL spectrum of LPE-CaO NPs

3.3 FTIR Analysis

The functional groups of LPE-CaO NPs and LPE were examined through FTIR spectra in Fig. 3a and Fig. 3b. The absorption band around 1438 cm^{-1} and the band around 874 cm^{-1} can be attributed to carbonate-related surface species, which may be due to the interaction of CaO with atmospheric CO_2 during processing or storage [19,20]. The peak at 1055 cm^{-1} indicates the C–O and C–O–C stretching vibrations of residual polysaccharide biomolecules of lemon peel powder, suggesting their role as reducing, capping and stabilising agents. The FTIR peak at 522 cm^{-1} describes the Ca – O stretching vibrations, validating the formation of CaO NPs. The FTIR spectrum of lemon peel powder exhibits a weak broad peak near 3323 cm^{-1} , attributed to the O – H stretching vibrations of hydroxyl groups, indicating the presence of polysaccharides with minimal moisture content [10]. A very small peak near 2928 cm^{-1} , assigned to the C–H stretching vibration [21]. The peaks at 1718 cm^{-1} and 1623 cm^{-1} correspond to the ester carbonyl groups of pectin [22]. The FTIR peaks at 1224 cm^{-1} and 1026 cm^{-1} were attributed to the C–O and C–O–C stretching vibrations, indicating cellulose and hemicellulose structures [23]. The low-frequency absorptions at 592 cm^{-1} and 505 cm^{-1} are in the fingerprint region and are linked to skeletal vibrations, like C–C and C–O bending, as well as ring deformations of polysaccharide and lignin frameworks. These spectral features are typical of complex biomaterials made from plants.

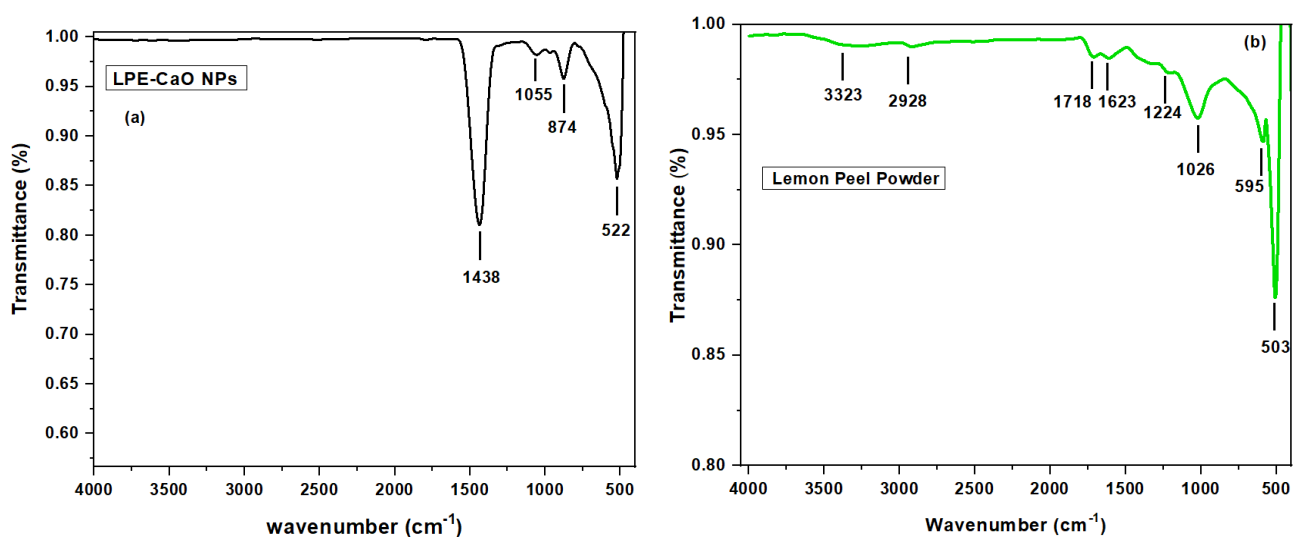


Fig. 3. FTIR spectrum: a) LPE-CaO NPs and b) Lemon Peel Powder

3.4 FESEM Analysis

FESEM images of biosynthesised LPE-CaO NPs show the nearly spherical morphology with moderate agglomeration in Fig. 4a and Fig. 4b. The particle sizes were measured by using ImageJ on the presented FESEM images of 104 individual particles and found in the range of 52.34-136.99 nm. The mean particle size was 87.88 ± 19.47 nm (mean $\pm$ standard deviation). The related distribution of particle size shows a moderate variation in particle size Fig. 4c.

Fig. 4d exhibits the elemental compositions of biosynthesised LPE-CaO NPs in the EDAX spectrum. The presence of Calcium (Ca) and Oxygen (O) elements in the EDAX spectrum confirms the formation of LPE-CaO NPs. The weight (%) and atomic (%) of Ca and O elements of LPE-CaO NPs are represented in Table 3.

Table 3. Elemental compositions of LPE-CaO NPs in the EDAX spectrum

Element	Weight (%)	Atomic (%)
O K	59.35	78.53
Ca K	40.65	21.47
Totals	100.00	100

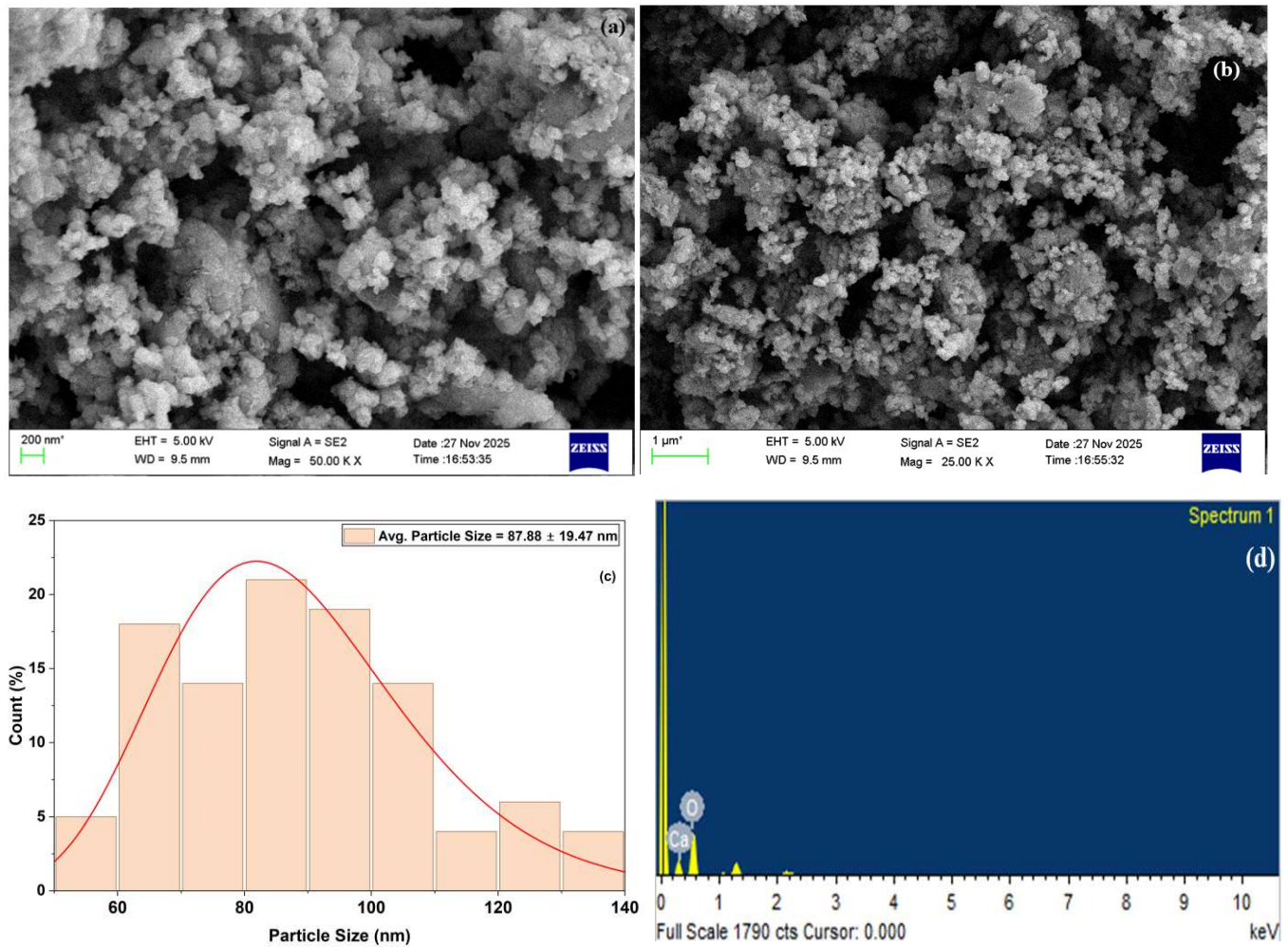


Fig. 4. a) and b) are the FESEM micrographs of LPE-CaO NPs, c) the average particle size distribution of LPE-CaO NPs, and d) the EDAX spectrum of LPE-CaO NPs.

3.5 Electrical properties

3.5.1 Electrical Impedance

The real part of impedance (Z') of synthesised LPE-CaO NPs was plotted against the frequency range 100-1 MHz with different temperatures from 303 K to 383 K, as shown in Fig. 5a. The mathematical expression of complex impedance is given as follows:

$$Z^*(\omega, T) = Z' + j Z'' \quad (5)$$

Where, ω is the angular frequency of the electric field, T is the temperature in Kelvin, and Z'' is the imaginary part of impedance.

From Fig. 5a, it is found that Z' decreases with increasing frequency and temperature. It exhibits constant behaviour in the higher frequency region due to the reduced contribution from space

charge and interfacial polarisation effects. The real part of impedance decreases with increasing temperature, depicting enhanced charge-carrier mobility, thermally activated nature of electrical transport and the NTCR in synthesised LPE-CaO NPs [11,24].

Fig. 5b represents the variation of $-Z''$ of LPE-CaO NPs as a function of frequency and temperature. It is observed that the values of $-Z''$ increased with frequency up to a maximum ($-Z''_{\max}$) and then decreased. The $-Z''_{\max}$ shifts towards higher frequencies as temperature increases [25]. It depicts both the type and strength of the thermal relaxation process in the synthesised material [26]. This process may be due to the presence of electrons and/or immobile species at lower temperatures as well as defects and vacancies at higher temperatures. [27].

The maximum relaxation frequencies ($f_{\max}$) and their relaxation time (τ) were calculated from the $-Z''_{\max}$ values (from Fig. 5b), using the relation (6). The variation of $\ln(f_{\max})$ vs $1000/T$ is shown in Fig. 5c. The relaxation process can be analysed by activation energy and relaxation time from the Arrhenius relation (7). It is found that the activation energy (E_{az}) and relaxation time (τ_0) are 0.0741 eV and 1.07×10^{-5} s, from Fig. 5c. The values of $f_{\max}$ and τ are presented in Table 4. The relaxation time values decrease with increasing temperature, demonstrating thermally activated relaxation [26].

$$\tau = \frac{1}{2\pi f_{\max}} \quad (6)$$

$$f_{\max} = f_0 \exp\left(\frac{-E_{az}}{k_B T}\right) \quad (7)$$

Where f_0 is the pre-exponential factor, K_B is the Boltzmann constant, and E_{az} is the activation energy calculated from impedance, and temperature in Kelvin.

Table 4. The maximum relaxation frequencies ($f_{\max}$) and their relaxation time (τ) values from the $-Z''$ vs frequency plot at different temperatures.

T (K)	$f_{\max}$ (Hz)	$\tau \times 10^{-4}$ (s)
303	900	1.7684
323	1000	1.5915
343	1200	1.3263
363	1400	1.1368

A Nyquist plot was drawn between Z' and Z'' in the temperature range 303 K to 383 K with a step size of 20 K, used to investigate the conduction mechanism of LPE-CaO NPs as shown in Fig. 5d. It is found that depressed semicircles indicate non-Debye relaxation and distribution of relaxation times, which are observed in all plots. Their maximum is moved to higher frequencies as temperatures rise. The plot indicates that the electrical conductivity exhibited thermally activated behaviour in synthesised LPE-CaO NPs [28]. The radius of the semicircle in the plot represents the magnitude of the circuit's impedance. As the temperature increases, the radius of the semicircle decreases, indicating that the impedance offered to the charge carriers is inversely proportional to temperature. This supports the confirmation of NTCR in the LPE-CaO NPs [11]. This demonstrates the reduction in the resistive contribution and enhanced thermally activated charge transport at the elevated temperatures. The Nyquist plots are modelled with an equivalent circuit ($R_1 + (CPE//R_2)$), where R_1 is the high-frequency series resistance, R_2 is the resistive contribution associated with the observed depressed semicircle response, CPE accounts for the deviation from ideal capacitive behaviour, and n is the CPE exponent, which is less than unity, indicating the non-ideal capacitive nature of the response. The values of R_1 , R_2 , CPE, and n are tabulated in Table 5. The resistances R_1 (Ω) and R_2 (Ω) decrease with increasing temperature, supporting the thermally activated nature of charge transport in LPE-CaO NPs [11,26].

Table 5. The equivalent circuit's electrical parameters were deduced from the Nyquist plot of LPE-CaO NPs.

T (K)	R_1 (Ω)	R_2 (Ω)	CPE ($S.s^n$)	n
303	3.238×10^7	2.159×10^8	1.463×10^{-11}	0.8441
323	3.148×10^7	1.544×10^8	8.288×10^{-12}	0.9032
343	2.528×10^7	8.320×10^7	4.692×10^{-11}	0.7933
363	1.076×10^7	4.156×10^7	2.710×10^{-11}	0.9118
383	2.816×10^6	1.317×10^7	1.357×10^{-11}	0.9223

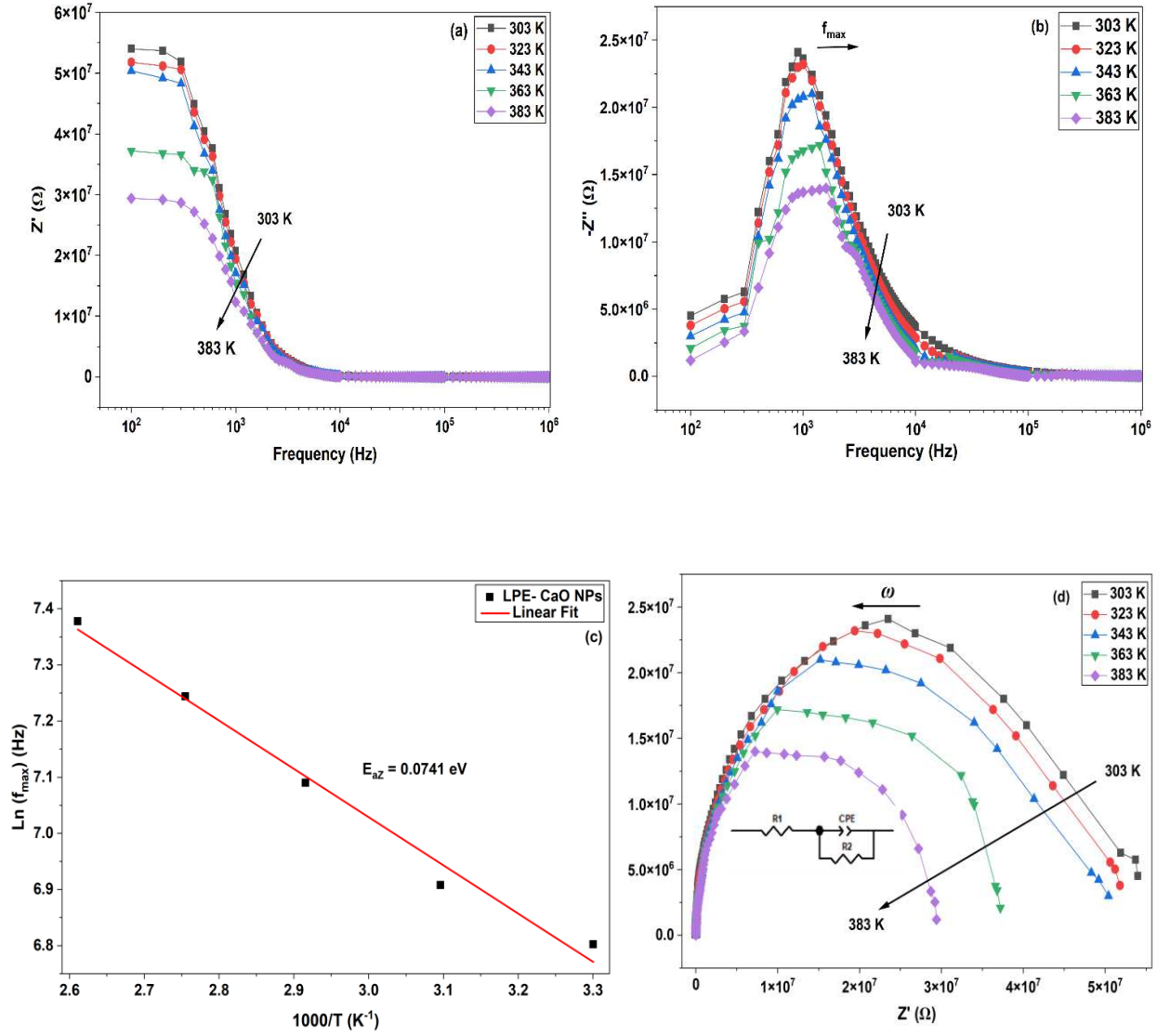


Fig. 5. a) and b) Real and Imaginary part of impedance vs frequency with different temperatures, c) Arrhenius plot, and d) Nyquist plot of LPE-CaO NPs.

3.5.2 Electric Modulus Analysis

The electric modulus analysis provides insights into the electrical relaxation behaviour of ion-conducting materials, offering the benefit of suppressing electrode polarisation effects [29]. The complex electric modulus is mathematically expressed as in relation (8). The real and imaginary parts of the electric modulus were determined using relations (9) and (10), respectively [25].

$$M^*(\omega, T) = M' + j M'' \quad (8)$$

$$M' = -\omega C_0 Z'' \quad (9)$$

$$M'' = \omega C_0 Z' \quad (10)$$

Where C_0 is the capacitance of free space (0.48 pF). The variation of the real part of electric modulus (M') as a function of frequency at the different temperatures in Fig. 6a. At low frequencies, M' tends towards zero at all temperatures, suggesting the electrode polarisation effect is significantly minimised and approaches a constant value at high frequencies, corresponding to bulk relaxation [30]. The temperature-dependent variation of M' is consistent with enhanced charge carrier mobility at elevated temperatures [31].

Fig. 6b represents the frequency dependence of the imaginary part of the electric modulus (M'') at the different temperatures. The M'' value at low frequencies describes the range in which charge carrier migration occurs through hopping between neighbouring sites [26]. The M'' values tend to be very small and nearly constant, reflecting that the charge carriers cannot follow the rapidly alternating field and thereby their localised motion persists. The relaxation peaks shift to higher frequencies with increasing temperature, indicating a reduction of relaxation time, confirming a thermally activated relaxation process related to charge carriers hopping between localised states.

The values of relaxation peaks ($f_{\max}$) corresponding to the M'' peak maximum and their relaxation time are presented in Table 6. The variation of $\ln(f_{\max})$ as a function of temperature is plotted by using the Arrhenius equation (11). The slope of the Arrhenius plot gives the activation energy E_{aM} is 0.073 eV, and the relaxation time is 0.952244×10^{-5} s.

$$f_{\max} = f_0 \exp\left(\frac{-E_{aM}}{k_B T}\right) \quad (11)$$

Where, E_{aM} is the activation energy evaluated from the relaxation peaks of the electric modulus, and f_0 is the pre-exponential factor.

Interestingly, the activation energies obtained from the impedance relaxation (~ 0.0741 eV) and from the electric-modulus relaxation (~ 0.073 eV) are very close. This close agreement indicates that the relaxation processes characteristic of the impedance and modulus representations have similar thermal activation energies. Therefore, the combined impedance and modulus results consistently support thermally activated electrical relaxation in bisynthesised LPE-CaO NPs.

Table 6. The maximum relaxation frequencies ($f_{\max}$) and their relaxation time (τ) values from the M'' vs frequency plot at different temperatures.

T (K)	$f_{\max}$ (Hz)	$\tau \times 10^{-4}$ (s)
303	1000	1.5915
323	1200	1.3263
343	1400	1.1368
363	1600	0.9947
383	1800	0.8846

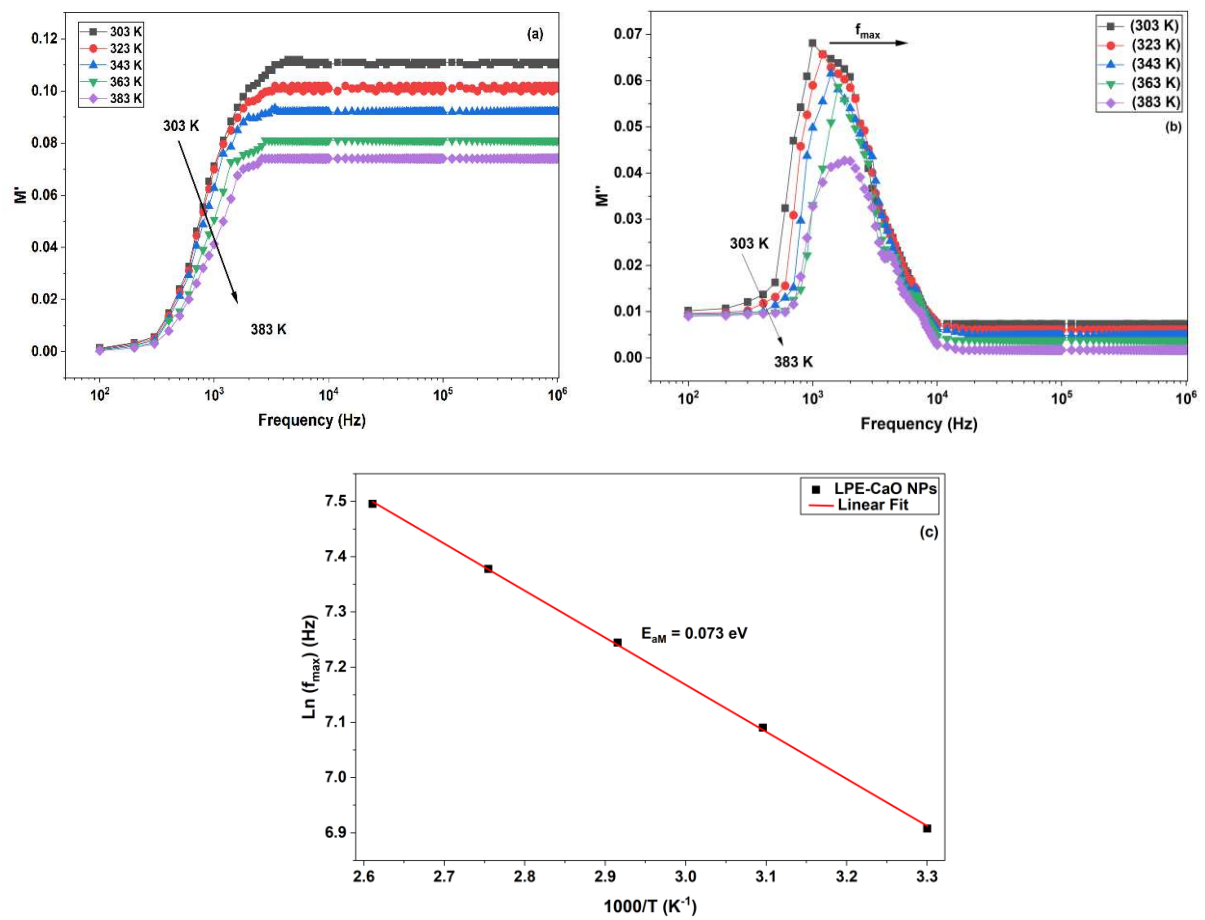


Fig. 6. a) and b) real and imaginary part of electric modulus as function of frequency at different temperatures, and c) Arrhenius plot of relaxation peaks of electric modulus.

3.5.3 Electrical Conductivity Analysis

The frequency-dependent AC conductivity of the LPE-CaO NPs was studied in the frequency range of 100 Hz–1 MHz at temperatures of 303–383 K. The total electrical conductivity

behaviour of the synthesised LPE-CaO NPs was plotted as a function of frequency over the temperature range of 303–383 K in Fig. 7, calculated using relation (12) [32].

$$\sigma_t = \frac{t.Z'}{A.[(Z')^2 + (Z'')^2]} \quad (12)$$

Where σ_t is the total electrical conductivity, t and A are the thickness and area of the pellet.

The conductivity increases with increasing frequency in the temperature range (303-383 K), as shown in Figure 7. The conductivity weakly depends on the frequency at lower frequencies and shows a strong increase at higher frequencies. Moreover, the conductivity increases systematically with increasing temperature in the entire frequency range, which confirms that the electrical transport in the LPE-CaO nanoparticles is thermally activated.

The observed frequency dependence is broadly consistent with Jonscher's universal power law for dispersive AC conduction in disordered materials. However, a clear frequency-independent DC conductivity plateau was not observed in the investigated frequency range (100 Hz- 1 MHz). Therefore, the present conductivity spectra do not permit the reliable extraction of unique Jonscher fitting parameters such as the DC conductivity (σ_{dc}), frequency exponent (n) and pre-exponential factor (A). These parameters were therefore not used for quantitative interpretation in the present study.

The increase in conductivity with temperature and frequency indicates enhanced mobility of the localised charge carriers under thermal activation. Thus, the conductivity behaviour is interpreted as a thermally activated, frequency-dependent electrical transport in the LPE-CaO nanoparticles. The AC conductivity data alone do not provide sufficient information to discriminate among different microscopic conduction models such as correlated barrier hopping (CBH), small polaron hopping (SPH), quantum mechanical tunnelling (QMT) or overlapping large polaron tunnelling (OLPT). Hence, no specific conduction mechanism is assigned based on AC conductivity analysis alone. Instead, the conductivity results are discussed together with the impedance and electric modulus analyses, which consistently suggest thermally activated electrical relaxation in the investigated material.

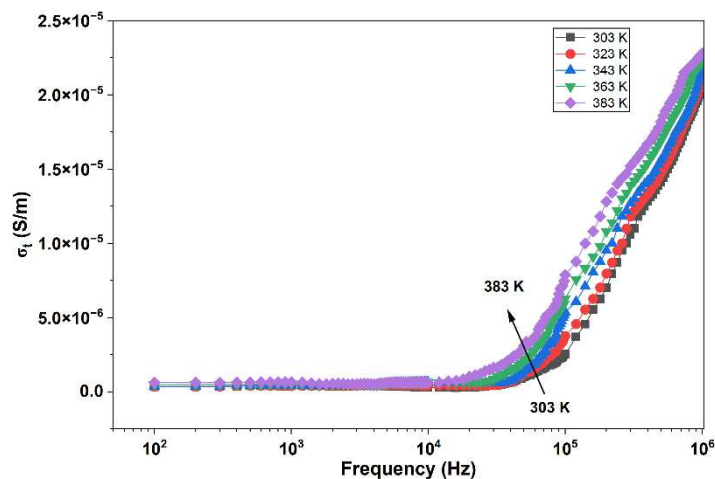


Fig. 7. Total electrical conductivity vs frequency at various temperatures

Conclusion

CaO nanoparticles were synthesised using LPE through ultrasonic-assisted coprecipitation. LPE-CaO NPs formed with an FCC structure without detectable secondary phase, observed by XRD analysis. The broad absorbance in LPE acts as a reducing and capping agent during the synthesis of LPE-CaO NPs, whereas the absorbance peak at 300 nm gives evidence of the formation of LPE-CaO NPs. The FTIR band of LPE-CaO NPs at 1055 cm^{-1} lies between the FTIR peaks of LPE at 1224 cm^{-1} and 1026 cm^{-1} , which were attributed to the C–O and C–O–C stretching vibrations, suggesting their role as reducing, capping and stabilising agents. FESEM images show the nearly spherical morphology, and the existence of Ca and O elements in the EDAX spectrum confirms the formation of LPE-CaO NPs. The electrical properties of LPE-CaO NPs were examined as a function of frequency and temperature. The real part of impedance decreases with an increase in temperature range (303 K– 383 K), indicating enhanced charge-carrier mobility and NTCR behaviour in synthesised LPE-CaO NPs. The Nyquist plots show depressed semicircles, indicating non-Debye relaxation and distribution of relaxation times. The relaxation frequencies were obtained from the imaginary part of impedance and electric modulus shift towards higher frequencies as temperature increases, accompanied by a corresponding decrease in relaxation time, confirming the thermally activated nature of the relaxation process. Furthermore, the activation energies obtained from Arrhenius plots of impedance and electric modulus are closely in agreement, supporting thermally activated relaxation behaviour in LPE-CaO NPs. The AC conductivity increases with increasing frequency and temperature, indicating thermally activated, frequency-dependent electrical transport. Overall, the combined results from structural, optical, morphological,

electrical impedance, electric modulus and electrical conductivity demonstrate that biosynthesised LPE-CaO NPs display frequency and temperature-dependent electrical properties, highlighting their potential in thermally activated electrical response applications.

Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication

Authors accept the publication policy of the journal.

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Credit authorship contribution statement

P. E. S. Bhaskar: Writing – original draft, investigation. **B. V. Vamsi Krishna:** Analysis of electrical properties. **R. K. Ramachandra:** Laboratory support and Project administration. **G. Lalitha Devi, Z. Spandana** and **N. Udaya Sri:** Review and editing. **M. V. S. Prasad:** Conceptualisation and supervision.

Declaration of 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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Highlights

- LPE-CaO nanoparticles exhibit frequency- and temperature-dependent electrical response.
- Impedance decreases with increasing frequency and temperature, indicating NTCR behaviour.
- Electrical impedance and electric modulus relaxation exhibit thermally activated behaviour.

- The activation energies obtained from electrical impedance and electric modulus relaxation are consistent.
- The AC conductivity increases with increasing frequency and temperature, indicating thermally activated and frequency-dependent electrical transport in LPE-CaO nanoparticles.

Supplementary Files

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