

Plant-Mediated Synthesis of LaCe and LaNd co-doped ZnO Nanoparticles: Investigation of Structural, Optical, Antibacterial and Anticancer Properties

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In the present investigation, the pure ZnO and rare earth metal co-doped ZnO nanoparticles, namely LaCe-ZnO and LaNd-ZnO nanoparticles, were successfully synthesized through an eco-friendly green synthesis approach using *Gymnema sylvestre* leaf extract. The plant extract acted as both reducing and stabilizing agent due to the presence of various bioactive phytochemicals such as flavonoids, phenols, tannins, saponins, triterpenoids, glycosides, steroids and glycerides. This green synthesis method offers a simple, cost-effective and environmentally benign alternative to conventional physical and chemical synthesis routes. The synthesized nanoparticles were characterized using X-ray diffraction (XRD), field emission scanning electron microscopy (FESEM), Energy dispersive X-ray analysis (EDAX), Fourier transform infrared spectroscopy (FTIR), UV-Visible spectroscopy and photoluminescence (PL) techniques to investigate their structural, morphological, elemental and optical properties. The antibacterial activity of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles was evaluated against Gram-positive bacteria (*Staphylococcus aureus* and *Streptococcus pneumoniae*) and Gram-negative bacteria (*Klebsiella pneumoniae*, *Shigella dysenteriae*, *Escherichia coli*, *Pseudomonas aeruginosa* and *Proteus vulgaris*) using the well diffusion method. Among the synthesized samples, LaCe-ZnO nanoparticles exhibited enhanced antibacterial activity compared with pure ZnO and LaNd-ZnO nanoparticles. Furthermore, *in vitro* cytotoxicity studies were carried out using A498 human kidney carcinoma cells and normal Vero kidney cells. The results revealed that LaCe-ZnO nanoparticles showed significant cytotoxic activity against A498 cancer cells with improved biological performance.

Keywords: Green synthesis, ZnO nanoparticles, Rare earth metals, *Gymnema sylvestre*, Antibacterial activity, Anticancer activity.

INTRODUCTION

Nanostructured materials have attracted considerable research interest owing to their distinctive optical, electrical, magnetic, photocatalytic and biomedical properties. Among various nanomaterials, metal oxide nanoparticles have received particular attention for their unique physico-chemical characteristics and potential applications in diverse technological and biomedical fields [1,2]. Zinc oxide (ZnO) is one of the most extensively investigated semiconductor metal oxides, owing

to its excellent chemical stability, relatively low toxicity, high biocompatibility and versatile functional properties. ZnO typically crystallizes in a hexagonal wurtzite structure and possesses a direct wide band gap of 3.37 eV and a high exciton binding energy of 60 meV, making it suitable for optoelectronic and biomedical applications [3,4].

ZnO nanoparticles have been extensively investigated for applications in solar cells, photocatalysis, electronics, light-emitting devices, transducers, sensors and biomedical systems. Doping and co-doping strategies have been employed to modify their

structural, optical, electrical and biological properties. Rare earth metal ions have attracted particular interest due to their distinctive electronic configurations and ability to influence defect structures and charge-carrier dynamics in semiconductor materials [5,6]. Rare earth co-doping can alter dopant solubility, carrier mobility and optical properties, providing opportunities to tailor the functional performance of ZnO-based nanomaterials.

ZnO nanoparticles have attracted attention for their antibacterial and anticancer properties, as well as their potential applications in drug delivery, bioimaging and cancer therapy [7]. Their antimicrobial activity is primarily associated with the generation of reactive oxygen species (ROS), which induce oxidative stress, damage bacterial cell membranes and ultimately cause cell death [8]. Rare earth co-doping has been investigated as a strategy to modify the biological activity and visible-light emission characteristics of ZnO nanoparticles, supporting their potential use in biomedical imaging and therapeutic applications [9].

Conventional chemical methods for nanoparticle synthesis often involve hazardous reagents and may generate toxic byproducts, raising concerns about environmental and human health risks [10]. These limitations have encouraged the development of environmentally benign nanofabrication strategies as sustainable alternatives to conventional synthesis methods. Plant-mediated synthesis has emerged as a promising approach, as plant extracts contain diverse bioactive constituents that facilitate nanoparticle formation by acting as reducing, surface-passivating and stabilizing agents during nucleation and growth [11–14].

Gymnema sylvestre, a medicinal plant belonging to the family *Asclepiadaceae*, has traditionally been used to treat diabetes, asthma, eye disorders and snake bites [15]. Its leaf extract contains various bioactive constituents, such as flavonoids, phenols, tannins, saponins, glycosides and gymnemic acid, which can facilitate the reduction and stabilization of metal ions during nanoparticle synthesis [16–18]. These phytochemicals may influence nanoparticle nucleation, growth and surface stabilization, contributing to the formation of stable nanostructures with potentially enhanced biological properties.

In present investigation, pure ZnO and rare earth co-doped ZnO nanoparticles, specifically LaCe-ZnO and LaNd-ZnO, were synthesized using a green, plant-mediated approach involving *G. sylvestre* leaf extract. The synthesized nanoparticles were characterized to examine their structural, morphological and optical properties. Their antibacterial activity against selected pathogenic bacterial strains and anticancer activity against A498 human kidney carcinoma cells were evaluated to assess their potential for biomedical applications. To the best of our knowledge, systematic investigations of La-Ce and La-Nd co-doped ZnO nanoparticles synthesized using the present green approach, particularly those examining their cytotoxicity against A498 human kidney carcinoma cells, remain limited.

EXPERIMENTAL

Characterization: The crystal structure and phase purity of the synthesized pure ZnO, LaCe co-doped ZnO and LaNd co-doped ZnO nanoparticles were investigated using X-ray diffraction (XRD) analysis performed on an X'PERT PRO PANalytical diffractometer with $\text{CuK}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$). The surface morphology, particle distribution and

microstructural characteristics of the samples were examined using field emission scanning electron microscopy (FESEM, Carl Zeiss Ultra 55), while the elemental composition and dopant incorporation were confirmed through energy-dispersive X-ray spectroscopy (EDAX) attached to the FESEM system. Fourier transform infrared (FTIR) spectroscopy was carried out in the spectral range of $400\text{--}4000 \text{ cm}^{-1}$ using a PerkinElmer spectrometer to identify the characteristic functional groups and chemical bonding present in the synthesized nanoparticles. The optical absorption behaviour and electronic transition characteristics were studied using a Perkin-Elmer Lambda 25 UV-Visible spectrophotometer. Furthermore, the photoluminescence (PL) properties of the samples were evaluated using a Horiba Jobin Yvon FLUOROMAX-4 spectrofluorometer equipped with a 450 W xenon lamp as the excitation source and the emission spectra were recorded over the wavelength range of $325\text{--}550 \text{ nm}$ to investigate the charge carrier recombination processes and defect-related luminescence characteristics of the nanoparticles.

Preparation of *Gymnema sylvestre* extract: Fresh and healthy leaves of *G. sylvestre* were collected from Manapparai Taluk, Tiruchirappalli District, India, during September 2025. The collected healthy *G. sylvestre* leaves were thoroughly washed with tap water followed by double-distilled water to remove dust and other surface impurities. Approximately 15 g of cleaned leaves were added to 150 mL of deionized water and heated at $80 \text{ }^\circ\text{C}$ for 1 h to prepare the leaf extract. The resulting extract was filtered using Whatman No. 1 filter paper and subsequently utilized for the green synthesis of nanoparticles.

Eco-friendly synthesis of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles: For the synthesis of pure ZnO nanoparticles, $0.1 \text{ M Zn(NO}_3)_2 \cdot 6\text{H}_2\text{O}$ was dissolved in 150 mL of the prepared *G. sylvestre* leaf extract. The reaction mixture was continuously stirred at $80 \text{ }^\circ\text{C}$ for 6 h until the formation of a yellow precipitate. The resulting precipitate was collected, dried at $120 \text{ }^\circ\text{C}$ for 2 h and subsequently annealed at $400 \text{ }^\circ\text{C}$ for 5 h to obtain pure ZnO nanopowder.

For the synthesis of LaCe co-doped ZnO nanoparticles, $0.002 \text{ M La(NO}_3)_3 \cdot 6\text{H}_2\text{O}$ and $0.001 \text{ M Ce(NO}_3)_3 \cdot 6\text{H}_2\text{O}$ were incorporated into a $0.097 \text{ M Zn(NO}_3)_2 \cdot 6\text{H}_2\text{O}$ solution. The resulting precursor mixture was dissolved in 150 mL of *G. sylvestre* leaf extract and continuously stirred at $80 \text{ }^\circ\text{C}$ for 6 h. The formed precipitate was subsequently dried at $120 \text{ }^\circ\text{C}$ for 2 h and annealed at $400 \text{ }^\circ\text{C}$ for 5 h to obtain LaCe-ZnO nanoparticles. Likewise, LaNd co-doped ZnO nanoparticles were prepared using lanthanum nitrate and neodymium nitrate precursors under the same experimental conditions.

Antibacterial assay: The antibacterial potential of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles was evaluated against selected Gram-positive (*Staphylococcus aureus* and *Streptococcus pneumoniae*) and Gram-negative (*Klebsiella pneumoniae*, *Shigella dysenteriae*, *Escherichia coli*, *Proteus vulgaris* *Pseudomonas aeruginosa*) bacterial strains using the agar well diffusion method. Mueller-Hinton agar (MHA) medium was sterilized, prepared and poured into Petri plates. Upon solidification, bacterial cultures were uniformly spread onto individual agar plates under sterile conditions. Nanoparticle suspensions prepared in DMSO at a concentration of

1.5 mg/mL were loaded into wells made in the agar plates. The plates were incubated at 37 °C for 24 h and antibacterial activity was quantified by measuring the inhibition zone diameters (mm). Amoxicillin was served as the reference standard for comparison.

Cell culture: The human kidney carcinoma cell line (A498) and normal Vero kidney cell line were cultured in Dulbecco's modified eagle medium (DMEM) supplemented with 10% fetal bovine serum (FBS), 100 µg/mL penicillin and 100 µg/mL streptomycin. The cultured cells were maintained at 37 °C in a humidified atmosphere containing 5% CO₂.

MTT cell viability assay: The *in vitro* cytotoxic activity of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles against A498 and Vero cell lines was evaluated using the MTT assay [19]. The synthesized nanoparticles were dispersed in sterile phosphate-buffered saline (PBS) and administered at various concentrations ranging from 10 to 100 µg/mL in serum-free Dulbecco's modified eagle medium (DMEM). The treated cells were incubated at 37 °C for 24 h. Following incubation, 20 µL of MTT solution (5 mg/mL in PBS) was added to each well and further incubated to facilitate the formation of formazan crystals. Subsequently, the absorbance was recorded at 570 nm using a microplate reader (Thermo-Fisher Scientific, USA). The percentage of cell viability and IC₅₀ values were calculated using GraphPad Prism 6.0 software. All experiments were carried out in triplicate and the percentage of inhibition was determined using the following equation:

$$\text{Inhibition (\%)} = \frac{A - B}{A} \times 100$$

where A = mean OD of untreated cells (control), B = mean OD of treated cells.

RESULTS AND DISCUSSION

Structural analysis: Fig. 1 shows the XRD patterns of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles synthesized using *G. sylvestre* leaf extract. The presence of sharp and intense diffraction peaks confirms the good crystalline nature of the synthesized nanoparticles. The major diffraction peaks observed at 2θ values of 31.72°, 34.39° and 36.20° correspond to the (100), (002) and (101) crystal planes of ZnO, respectively. Additional diffraction peaks appearing at 47.48°, 56.51°, 62.82°, 67.86°, 69.13°, 72.55° and 77.01° were indexed to the (102), (110), (103), (112), (201), (004) and (202) planes of hexagonal wurtzite ZnO structure. The obtained diffraction pattern closely matches the standard JCPDS data (Card No. 36-1451), which confirms the formation of phase-pure ZnO nanoparticles without detectable secondary impurity phases [20].

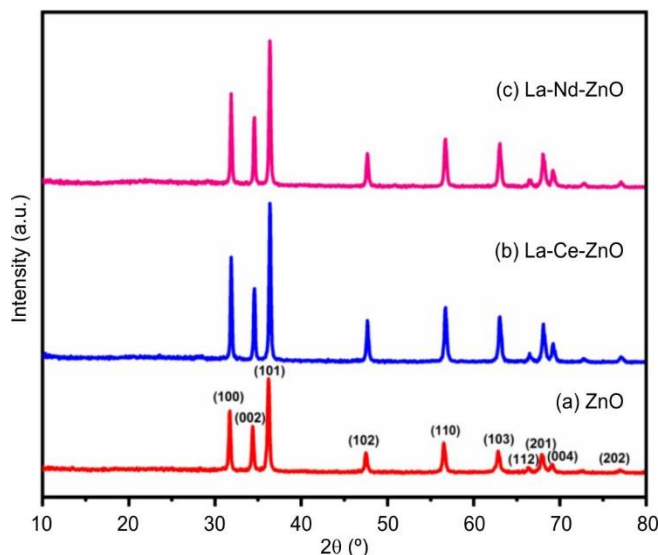


Fig. 1. XRD patterns of (a) pure ZnO, (b) LaCe-ZnO and (c) LaNd-ZnO nanoparticles

The average crystallite size of the synthesized nanoparticles was determined using the Debye-Scherrer equation:

$$D = \frac{0.9\lambda}{\beta \cos \theta} \quad (1)$$

where D represents the crystallite size, λ is the wavelength of CuKα radiation (1.5406 Å), β is the full width at half maximum (FWHM) and θ is the Bragg diffraction angle.

The calculated crystallite sizes of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles were found to be 38 nm, 32 nm and 31 nm, respectively. Furthermore, important structural parameters such as lattice constants, axial ratio (c/a), atomic packing factor, positional parameter (u) and bond length (L) were calculated using standard equations reported in the literature [21]. The obtained values are summarized in Table-1.

FT-IR analysis: Fig. 2 presents the FTIR spectra of pristine ZnO and LaCe-ZnO and LaNd-ZnO nanoparticles synthesized through a green route using *G. sylvestre* leaf extract. The spectra exhibit characteristic absorption bands associated with surface functional groups and Zn–O vibrations. The broad bands at 3420 3398 and 3408 cm⁻¹ are attributed to O–H stretching vibrations of surface-adsorbed water and hydroxyl groups [22]. The bands at 2978-2924 and 2426 cm⁻¹ are associated with asymmetric and symmetric C–H stretching vibrations of alkyl groups and may indicate the presence of residual organic species [22]. The bands at 1571 1645 and 1647 cm⁻¹ are assigned to C=O or asymmetric COO⁻ vibrations and H–O–H bending. The bands at 1421 1497 and 1384 cm⁻¹ are primarily associated with O–H bend-

TABLE-1
XRD PARAMETERS VALUES OF PURE ZnO, LaCe-ZnO AND LaNd-ZnO NANOPARTICLES

Samples	Lattice parameter values (nm)		Atomic packing factor (c/a)	Volume (V) (Å) ³	cos φ	Position parameter (u)	Bond length (Zn-O) (Å)	Average crystallite size (nm)
	a	c						
Pure ZnO NPs	0.3255	0.5215	1.6017	47.876	0.9459	0.3798	1.5569	38
LaCe-ZnO NPs	0.3240	0.5188	1.6012	47.129	0.9469	0.3799	1.5519	32
LaNd-ZnO NPs	0.3240	0.5190	1.6018	47.147	0.9464	0.3798	1.5520	31

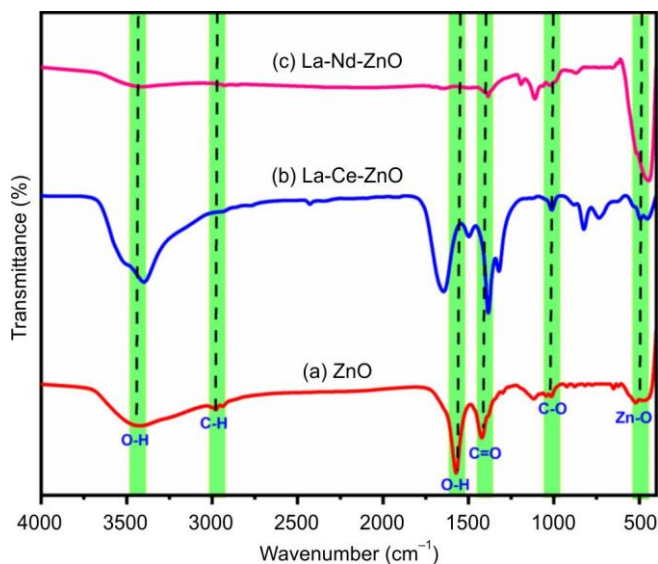


Fig. 2. FTIR spectra of (a) pure ZnO, (b) LaCe-ZnO and (c) LaNd-ZnO nanoparticles

ing and may include contributions from residual nitrate-related vibrations [23]. The absorption bands within the 1111-1012 cm^{-1} region are attributed to C–O stretching vibrations [23]. The bands at 878 880 and 869 cm^{-1} may be associated with O–H bending or secondary lattice vibrations. The prominent bands at 467 452 and 443 cm^{-1} for pristine ZnO LaCe-ZnO and LaNd-ZnO respectively are the characteristic of Zn–O stretching vibrations and support the formation of the ZnO lattice [24]. The slight shift in the Zn–O absorption band following La/Ce and La/Nd incorporation suggests changes in the local lattice environment.

Morphological analysis: Fig. 3 shows the FESEM images of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles synthesized using *G. sylvestre* leaf extract. The micrographs reveal that the synthesized nanoparticles possess predominantly spherical-like morphology with slight agglomeration. The average particle sizes were estimated to be approximately 138 nm for pure ZnO, 67 nm for LaCe-ZnO and 70 nm for LaNd-ZnO nanoparticles. Compared to pure ZnO, the co-doped samples exhibited reduced particle size and thickness. This reduction may be attributed to the incorporation of rare earth metal ions such as La^{3+} , Ce^{3+} and Nd^{3+} into the ZnO lattice, which induces lattice distortion and influences the growth behaviour of the nanoparticles. The observed variations in particle size and morphology can be attributed to the differences in ionic radii between the dopant ions, La^{3+} (1.061 Å), Ce^{3+} (1.034 Å) and Nd^{3+} (0.995 Å) and the host Zn^{2+} ions. The incorporation of these rare-earth ions into the ZnO lattice influences the surface morphology and structural characteristics of the synthesized nanoparticles [21].

The elemental composition and chemical purity of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles were analyzed using energy dispersive X-ray Analysis (EDAX) and the corresponding spectra are shown in Fig. 4. The EDAX results confirmed the presence of Zn and O elements in pure ZnO nanoparticles, with elemental percentages of 83.90% and 16.10%, respectively. The characteristic peaks associated with La Ce and Nd were observed in the co-doped samples,

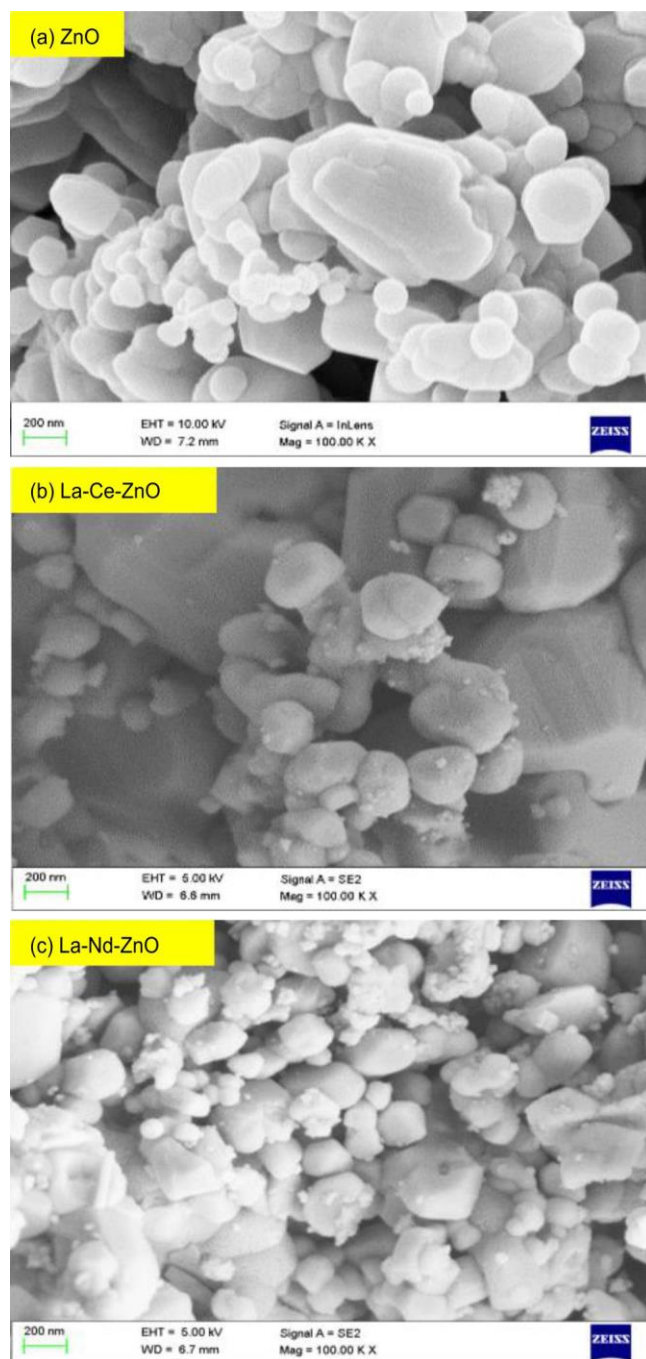


Fig. 3. FESEM images of (a) pure ZnO, (b) LaCe-ZnO and (c) LaNd-ZnO nanoparticles

which support the incorporation of rare earth metal ions into the ZnO lattice. The dopant concentration for both LaCe-ZnO and LaNd-ZnO nanoparticles was found to be approximately 1.54%. The absence of additional impurity peaks in the spectra confirms the high purity of the synthesized nanoparticles. The detailed elemental composition data are provided in Table-2.

Optical studies: The UV-visible absorption spectra of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles are shown in Fig. 5. Prior to analysis, 3 mg of each sample was dispersed in distilled water and ultrasonicated for 20 min to obtain a homogeneous suspension. The synthesized nanoparticles

TABLE-2
ELEMENTAL COMPOSITION OF PURE ZnO, LaCe-ZnO AND LaNd-ZnO NANOPARTICLES

Samples	Zn (At %)	O (At %)	Dopant concentration (At %)		Total (%)
Pure ZnO NPs	83.90	16.10	—		100
LaCe-ZnO NPs	83.41	15.05	1.04 (La)	0.50 (Ce)	100
LaNd-ZnO NPs	82.40	16.06	1.06 (La)	0.48 (Nd)	100

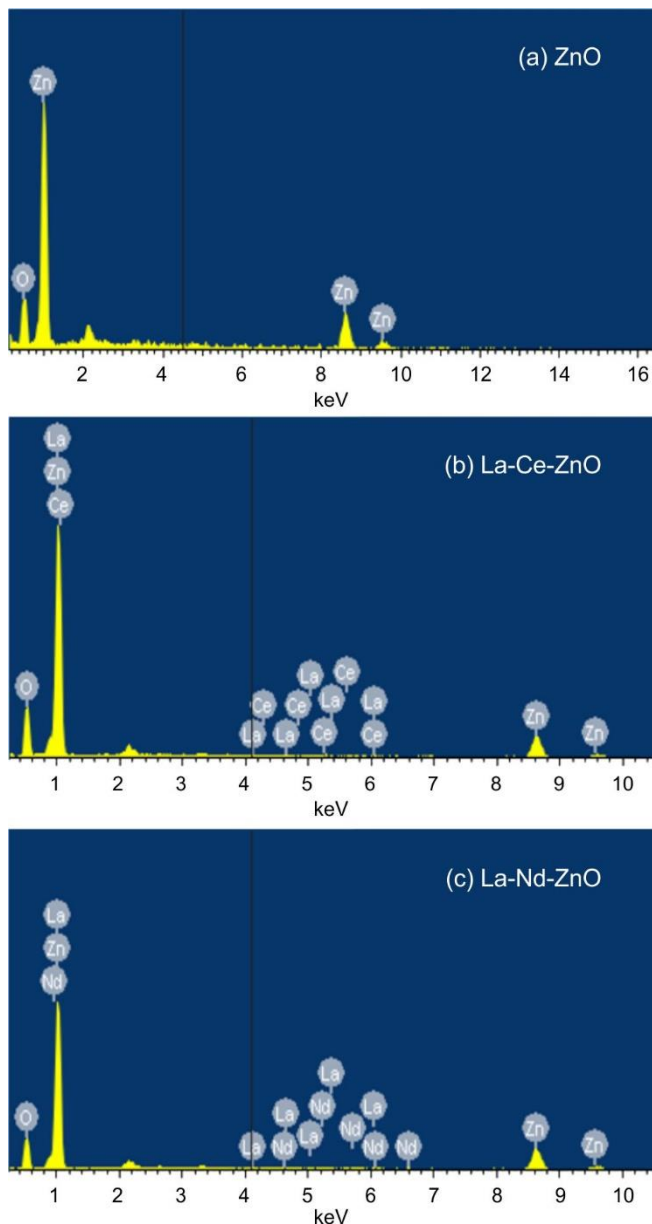


Fig. 4. EDAX spectra of (a) pure ZnO, (b) LaCe-ZnO and (c) LaNd-ZnO nanoparticles

exhibited strong absorption peaks at 378 nm, 391 nm and 397 nm for pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles, respectively. Compared with pure ZnO, the absorption edges of the co-doped samples showed a noticeable shift, indicating the influence of rare earth metal doping on the optical properties of ZnO nanoparticles.

The optical band gap energy (E_g) was calculated using the Tauc relation:

$$(\alpha h\nu)^2 = B(h\nu - E_g)^{1/2} \quad (1)$$

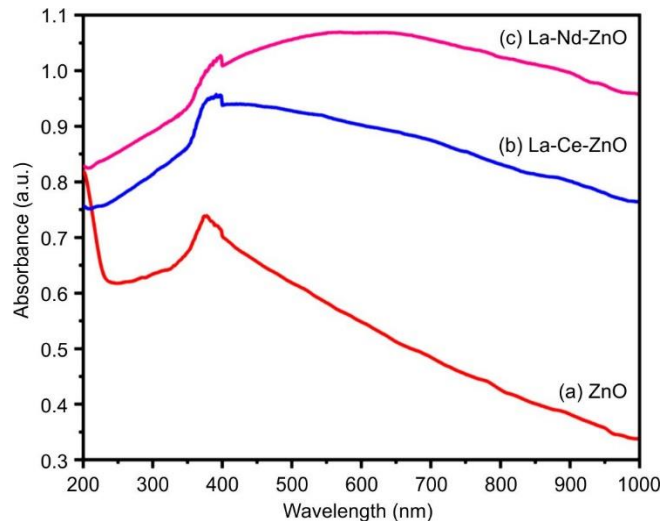


Fig. 5. UV-visible absorption spectra of (a) pure ZnO, (b) LaCe-ZnO and (c) LaNd-ZnO nanoparticles

where α is the absorption coefficient, $h\nu$ is the photon energy, B is a constant and E_g represents the optical band gap energy. Since ZnO is a direct band gap semiconductor, plots of $(\alpha h\nu)^2$ versus $h\nu$ were constructed, as shown in Fig. 6. The optical band gap values were estimated by extrapolating the linear region of the Tauc plots to the $(\alpha h\nu)^2 = 0$.

The optical band gap energies were determined to be 3.40 eV for pure ZnO, 2.75 eV for LaCe-ZnO and 2.5 eV for LaNd-ZnO nanoparticles. The red shift in the absorption edge and the reduction in band gap may be associated with the formation of oxygen vacancies and the introduction of additional energy levels within the ZnO band gap upon doping. These structural modifications may alter the average inter-atomic distances and electronic structure of ZnO [25]. The oxygen vacancies can facilitate electron capture by surface-adsorbed oxygen molecules and promote the generation of reactive oxygen species. Such processes may contribute to enhanced antibacterial and anticancer activities. Interactions between the localized f -electrons of rare earth ions and the electronic states of ZnO may further modify the conduction and valence band structures and contribute to band gap narrowing [26-28].

Optical emission studies: The photoluminescence (PL) spectra of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles, recorded at an excitation wavelength of 325 nm. The PL spectrum of pure ZnO nanoparticles exhibited characteristic emission peaks at 421, 451, 465, 489 and 516 nm (Fig. 7). The violet emission band centered at 421 nm is attributed to electronic transitions from shallow donor levels associated with zinc interstitial defects to the valence band [29]. The blue emission bands observed at 451 and 465 nm are assigned to singly ionized zinc vacancy defects [30].

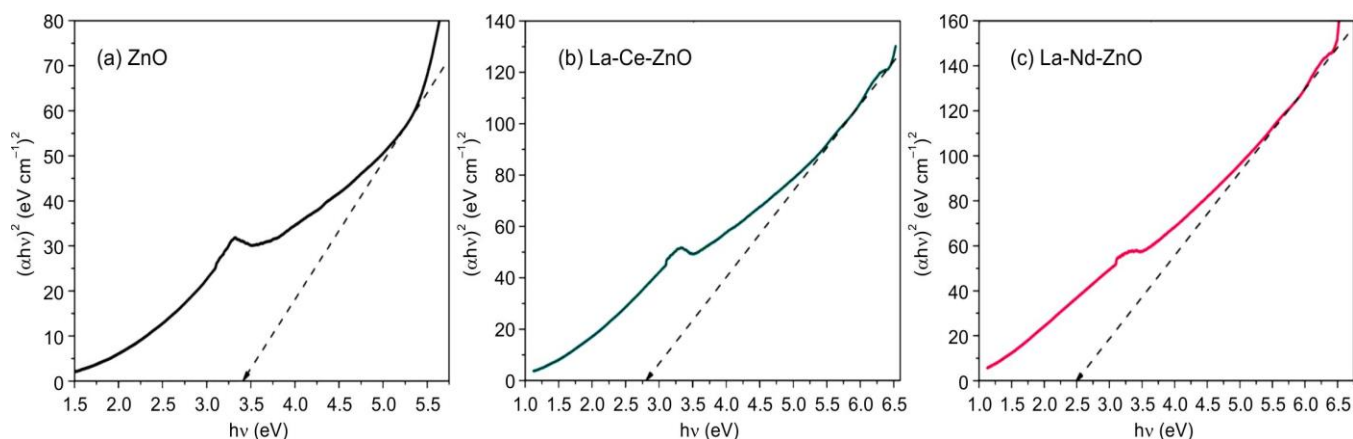
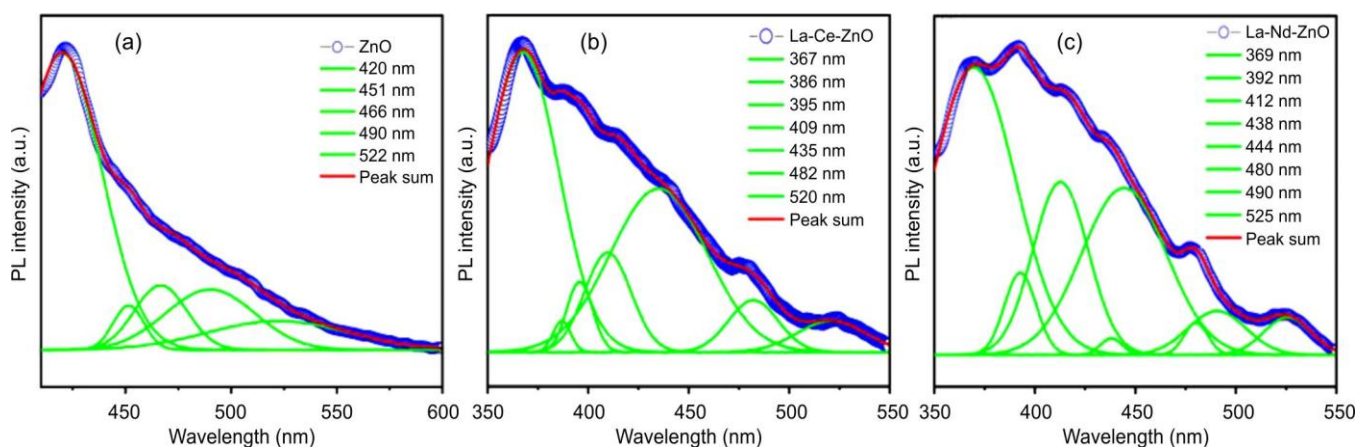
Fig. 6. Tauc plots of $(\alpha h\nu)^2$ versus $h\nu$ for (a) pure ZnO, (b) LaCe-ZnO and (c) LaNd-ZnO nanoparticles

Fig. 7. PL emission spectra of (a) pure ZnO, (b) LaCe-ZnO and (c) LaNd-ZnO nanoparticles

The blue–green emission band observed around 489 nm is attributed to defect states associated with oxygen vacancies and interstitial oxygen transitions [31]. The green emission peak centered at 516 nm corresponds to singly ionized oxygen vacancies within the ZnO lattice [32,33]. Compared with pure ZnO nanoparticles, the co-doped samples exhibited clear variations in emission intensity and peak position. The green emission band of LaNd-ZnO nanoparticles exhibited a red shift to 525 nm. The observed changes in the PL spectra suggest that rare earth doping may suppress electron–hole pair recombination and improve the separation of photogenerated charge carriers. This effect may contribute to enhanced photocatalytic activity. Compared with pristine ZnO and other La^{3+} - and Ce^{3+} -doped ZnO nanoparticles, Nd-doped ZnO exhibited pronounced quenching of the PL emission intensity. This observation suggests that rare earth ion incorporation may improve charge-carrier separation efficiency and potentially enhance antibacterial activity [34]. The corresponding PL emission data are summarized in Table-3.

Antibacterial activity: The antibacterial activity of green-synthesized pristine ZnO and LaCe-ZnO and LaNd-ZnO nanoparticles was evaluated against selected human pathogenic bacterial strains at a concentration of 1.5 mg/mL. Among the synthesized samples LaCe-ZnO nanoparticles exhibited the highest antibacterial activity compared with pristine ZnO and LaNd-ZnO (Fig. 8). This enhanced activity

ZnO (nm)	LaCe-ZnO (nm)	LaNd-ZnO (nm)
–	367	369
–	386	392
421	395	412
451	409	438
465	435	444
489	482	480
–	–	490
516	520	525

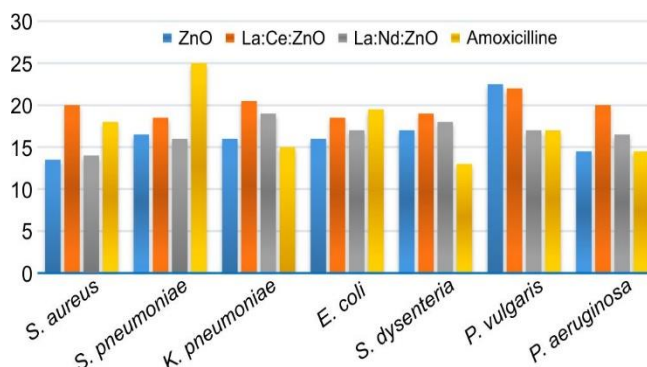


Fig. 8. Zone of inhibition of pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles against selected bacterial strains

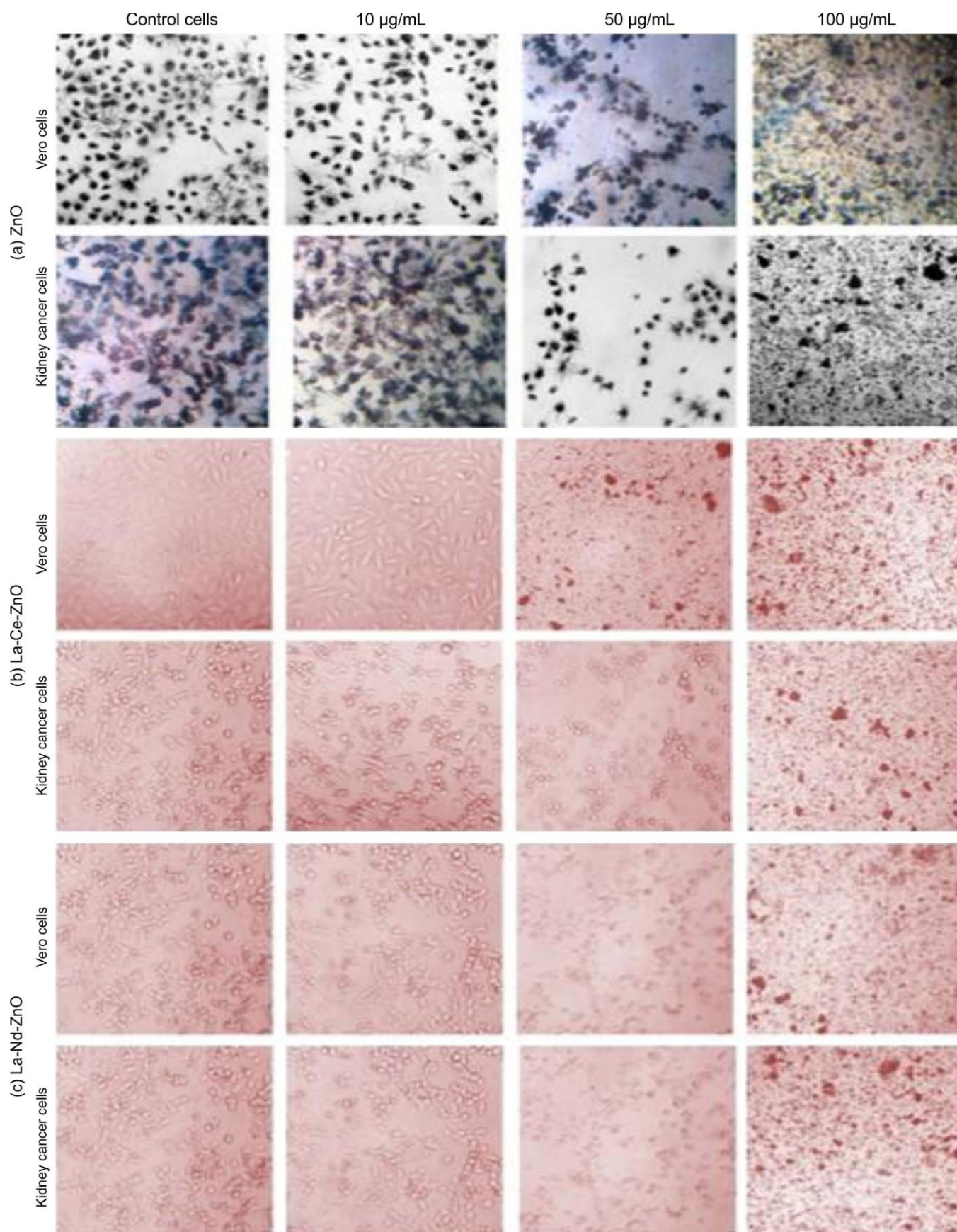


Fig. 9. Morphological changes in A498 and Vero cells treated with pure ZnO, LaCe-ZnO and LaNd-ZnO nanoparticles at different concentrations

may be associated with reactive oxygen species (ROS) generation and the presence of oxygen vacancies and surface defects along with the release of Zn^{2+} ions from the nanoparticle surface [24]. These factors may promote bacterial membrane damage and inhibit microbial growth.

The antibacterial activity of nanoparticles is influenced by their crystallite size and surface morphology. XRD analysis revealed crystallite sizes of 38 nm for pristine ZnO and 32 nm and 31 nm for LaCe-ZnO and LaNd-ZnO respectively. Previous studies [21,35] have reported enhanced antibacterial activity in nanoparticles with crystallite sizes of approximately 30-35 nm. In this study, LaCe-ZnO nanoparticles with a crystallite size of 32 nm exhibited the highest antibacterial activity among the synthesized samples.

As FESEM analysis also revealed a spherical-like morphology for the synthesized nanoparticles. LaCe-ZnO nanoparticles displayed comparatively rough and uneven surface features which may promote stronger interactions with bacterial cell walls. Such surface irregularities may facilitate membrane disruption and contribute to enhanced antibacterial activity [36]. In comparison nanoparticles with smoother surfaces exhibited relatively lower antibacterial activity.

Anticancer activity: The anticancer activity of pristine ZnO and LaCe-ZnO and LaNd-ZnO nanoparticles was evaluated against A498 human kidney carcinoma cells and normal Vero cells. Cytotoxicity was assessed at concentrations ranging from 10 to 100 $\mu\text{g/mL}$ using the MTT assay. The IC_{50} values of pristine ZnO LaCe-ZnO and LaNd-ZnO nanoparticles against A498 cells were 41.74 39.16 and 40.72 $\mu\text{g/mL}$, respectively. The corresponding IC_{50} values against Vero cells were 55.27 57.24 and 53.27 $\mu\text{g/mL}$ after 24 h of treatment ($p \leq 0.05$). Among the tested samples LaCe-ZnO nanoparticles exhibited the lowest IC_{50} value against A498 cells indicating comparatively greater cytotoxic activity toward the cancer cells under the investigated conditions.

Morphological changes in the treated cells were examined using light microscopy at concentrations of 10, 50 and 100 $\mu\text{g/mL}$ (Fig. 9). The treated cancer cells exhibited clear morphological alterations such as cell shrinkage irregular morphology and reduced cell density. These changes are consistent with nanoparticle-induced cytotoxic effects. The enhanced anticancer activity of LaCe-ZnO nanoparticles may be associated with increased ROS generation and changes in redox activity following rare earth metal incorporation into the ZnO lattice. The reduced band gap observed in the doped nanoparticles may facilitate the generation of photogenerated charge carriers under suitable irradiation conditions and influence ROS production [36]. Reactive oxygen species such as hydrogen peroxide (H_2O_2) superoxide radicals ($\text{O}_2^{\bullet-}$) and hydroxyl radicals ($^{\bullet}\text{OH}$) can induce oxidative stress and damage essential cellular components including DNA proteins and lipids. La^{3+} and Ce^{3+} ions may further influence cellular processes through interactions with proteins and respiratory enzymes. Such interactions could contribute to the oxidative stress and nanoparticle-induced cytotoxicity. The comparatively lower IC_{50} value of LaCe-ZnO against A498 cells supports its higher cytotoxic activity among the tested samples under the experimental conditions used.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors' own. The authors reviewed and edited the content and take full responsibility for the published work.

REFERENCES

1. K. Kannan, D. Radhika, K.K. Sadasivuni, K.R. Reddy and A.V. Raghu, *Adv. Colloid Interface Sci.*, **281**, 102178 (2020); <https://doi.org/10.1016/j.cis.2020.102178>
2. B. Lee, Y. Lee, N. Lee, D. Kim and T. Hyeon, *Nat. Rev. Mater.*, **10**, 252 (2025); <https://doi.org/10.1038/s41578-024-00767-x>
3. Q. Chen and J. Wang, *Phys. Chem. Chem. Phys.*, **15**, 17793 (2013); <https://doi.org/10.1039/c3cp52391h>
4. S.Z. Wu, H.L. Yang, X.G. Xu, J. Miao and Y. Jiang, *J. Phys. Conf. Ser.*, **263**, 012022 (2011); <https://doi.org/10.1088/1742-6596/263/1/012022>
5. S. Huang, Q. Xiao, H. Zhou, D. Wang and W. Jiang, *J. Alloys Compd.*, **486**, L24 (2009); <https://doi.org/10.1016/j.jallcom.2009.07.033>
6. W. An, X. Wu and X.C. Zeng, *J. Phys. Chem. C Nanomater. Interfaces*, **112**, 5747 (2008); <https://doi.org/10.1021/jp711105d>
7. D. Das, B.C. Nath, P. Phukon, A. Kalita and S.K. Dolui, *Colloids Surf. B Biointerfaces*, **111**, 556 (2013); <https://doi.org/10.1016/j.colsurfb.2013.06.041>
8. S. Singh, K.C. Barick and D. Bahadur, *CrystEngComm*, **15**, 4631 (2013); <https://doi.org/10.1039/c3ce27084j>
9. J. Lang, Q. Han, J. Yang, C. Li, X. Li, L. Yang, Y. Zhang, M. Gao, D. Wang and J. Cao, *J. Appl. Phys.*, **107**, 074302 (2010); <https://doi.org/10.1063/1.3318613>
10. G. Singhal, R. Bhavesh, K. Kasariya, A.R. Sharma and R.P. Singh, *J. Nanopart. Res.*, **13**, 2981 (2011); <https://doi.org/10.1007/s11051-010-0193-y>
11. M. Sundraranjan, S. Ambika and K. Bharathi, *Adv. Powder Technol.*, **26**, 1294 (2015); <https://doi.org/10.1016/j.apt.2015.07.001>
12. H. Upadhyaya, S. Shome, R. Sarma, S. Tewari, M.K. Bhattacharya and S.K. Panda, *Am. J. Plant Sci.*, **9**, 1279 (2018); <https://doi.org/10.4236/ajps.2018.96094>
13. R. Khan, M. Khan, Hameedullah, A. Ansari, Lohani, R. Khan, I. Ahmad, F.M. Husain, W. Khan and M. Alam, *Int. J. Nanomedicine*, **9**, 853 (2014); <https://doi.org/10.2147/IJN.S47351>
14. W. Zhang, S. Bao and T. Fang, *Sci. Rep.*, **6**, 24839 (2016); <https://doi.org/10.1038/srep24839>
15. T. Dheepakamalani, T. Thiagasundaram, V. Thanigavelan, V. Kaliyamurthi, S. Elansekaran and M. Jegadeesan, *Int. J. Pharm. Phytopharmacol. Res.*, **2**, 143 (2012).
16. P. Vijayakumar and A. Jafar Ahamed, *J. Adv. Appl. Sci. Res.*, **1**, 1 (2017); <https://doi.org/10.46947/joaasr18201763>

17. P. Tiwari, B.N. Mishra and N.S. Sangwan, *BioMed Res. Int.*, **2014**, 830285 (2014);
<https://doi.org/10.1155/2014/830285>
18. A. Jafar Ahamed and P. Vijayakumar, *Int. J. Adv. Sci. Technol.*, **5**, 67 (2017).
19. M. Carofiglio, S. Barui, V. Cauda and M. Laurenti, *Appl. Sci.*, **10**, 5194 (2020);
<https://doi.org/10.3390/app10155194>
20. J. Iqbal, X. Liu, H. Zhu, Z.B. Wu, Y. Zhang, D. Yu and R. Yu, *Acta Mater.*, **57**, 4790 (2009);
<https://doi.org/10.1016/j.actamat.2009.06.056>
21. A.S. Haja Hameed, C. Karthikeyan, S. Sasikumar, V. Senthil Kumar, S. Kumaresan and G. Ravi, *J. Mater. Chem. B*, **1**, 5950 (2013);
<https://doi.org/10.1039/c3tb21068e>
22. G. Xiong, U. Pal, J.G. Serrano, K.B. Ucer and R.T. Williams, *Phys. Status Solidi., C Curr. Top. Solid State Phys.*, **3**, 3577 (2006);
<https://doi.org/10.1002/pssc.200672164>
23. M. Al Bitar, B. Hassanieh, R. Awad and M. Khalil, *Saudi J. Biol. Sci.*, **30**, 103608 (2023);
<https://doi.org/10.1016/j.sjbs.2023.103608>
24. A.S.H. Hameed, C. Karthikeyan, A.P. Ahamed, N. Thajuddin, N.S. Alharbi, S.A. Alharbi and G. Ravi, *Sci. Rep.*, **6**, 24312 (2016);
<https://doi.org/10.1038/srep24312>
25. S. Irtiqah and A. Rahman, *Russ. J. Appl. Chem.*, **93**, 1906 (2020);
<https://doi.org/10.1134/S1070427220120137>
26. M. Bouloudenine, N. Viart, S. Colis, J. Kortus and A. Dinia, *Appl. Phys. Lett.*, **87**, 052501 (2005);
<https://doi.org/10.1063/1.2001739>
27. P. Koidl, *Phys. Rev., B, Solid State*, **15**, 2493 (1977);
<https://doi.org/10.1103/PhysRevB.15.2493>
28. S.S. Kumar, P. Venkateswarlu, V.R. Rao and G.N. Rao, *Int. Nano Lett.*, **3**, 30 (2013);
<https://doi.org/10.1186/2228-5326-3-30>
29. X.M. Fan, J.S. Lian, L. Zhao and Y.H. Liu, *Appl. Surf. Sci.*, **252**, 420 (2005);
<https://doi.org/10.1016/j.apsusc.2005.01.018>
30. S.K. Mishra, R.K. Srivastava, S.G. Prakash, R.S. Yadav and A.C. Panday, *Opto-Electron. Rev.*, **18**, 467 (2010);
<https://doi.org/10.2478/s11772-010-0037-4>
31. N. Varghese, L.S. Panchakarla, M. Hanapi, A. Govindaraj and C.N.R. Rao, *Mater. Res. Bull.*, **42**, 2117 (2007);
<https://doi.org/10.1016/j.materresbull.2007.01.017>
32. N. Kumar, A. Dorfman and J.I. Hahm, *J. Nanosci. Nanotechnol.*, **5**, 1915 (2005);
<https://doi.org/10.1166/jnn.2005.422>
33. D.M. Bagnall, Y.F. Chen, M.Y. Shen, Z. Zhu, T. Goto and T. Yao, *J. Cryst. Growth*, **184–185**, 605 (1998);
[https://doi.org/10.1016/S0022-0248\(97\)00526-5](https://doi.org/10.1016/S0022-0248(97)00526-5)
34. S. Zandi, P. Kameli, H. Salamati, H. Ahmadvand and M. Hakimi, *Physica B*, **406**, 3215 (2011);
<https://doi.org/10.1016/j.physb.2011.05.026>
35. G.X. Tong, F.F. Du, Y. Liang, Q. Hu, R.N. Wu, J.G. Guan and X. Hu, *J. Mater. Chem. B*, **1**, 454 (2013);
<https://doi.org/10.1039/C2TB00132B>
36. K. Vijayalakshmi and D. Sivaraj, *RSC Adv.*, **6**, 9663 (2016);
<https://doi.org/10.1039/C5RA28125C>