

Eco-Friendly Combustion Synthesis of ZnO Nanoparticles Using Aloe Vera Latex: Structural and Optical Properties

Hussam Musleh

`hussam.musleh@univ-littoral.fr`

Université du littoral côte d'opale

Abdelylah Daoudi

Université du littoral côte d'opale

Samy Mansy

University College of Science and Technology - Khan Younis

Naji AlDahoudi

Université de Picardie Jules Verne

Abdelilah Lahmar

Université de Picardie Jules Verne

Yahia Boussoualem

Université du littoral côte d'opale

Khaoula Ferchichi

Université du littoral côte d'opale

Article

Keywords: ZnO-NPS, Solution combustion, Aloe-vera, Williamson-Hall model and Size-strain model

Posted Date: September 8th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10813266/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Eco-Friendly Combustion Synthesis of ZnO Nanoparticles Using Aloe Vera Latex: Structural and Optical Properties

Hussam Musleh^{1,2,*}, Abdelylah Daoudi¹, Samy Mansy³, Naji AlDahoudi^{2,4},
Abdelilah Lahmar⁴, Yahia Boussoualem¹ and Khaoula Ferchichi¹

¹ University Littoral Côte d'Opale, UR 4476, UDSMM, Unité de Dynamique et Structure des Matériaux Moléculaires, F-59140 Dunkerque, France.

² Al Azhar University-Gaza, Physics Department, Gaza, Palestine .

³ University College of Science and Technology – Khan Younis, Department of Engineering Sciences and Applied Arts. Gaza, Palestine.

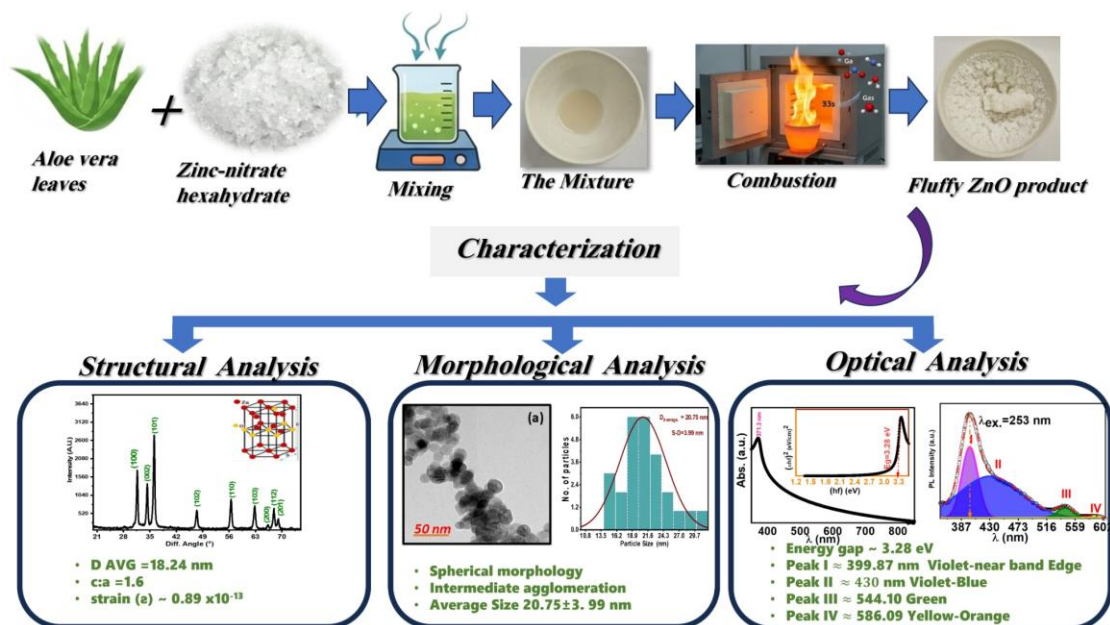
⁴ Condensed Matter Physics Laboratory (LPMC), University of Picardie Jules Verne, 33 Rue Saint Leu, 80000 Amiens, France.

*Corresponding Authors Musleh Hussam (hussam.musleh@univ-littoral.fr)

Abstract

This research outlines an eco-friendly and economical method for synthesizing ZnO-NPS using a solution combustion technique. Zinc nitrate hexahydrate was utilized as the metal precursor, and *Aloe-vera* leaf latex, known for its biocompatibility, served as a natural combustion fuel without any other chemical additives. The X-RD analysis indicated the formation of a hexagonal wurtzite crystal structure with an average crystallite size of around 18 nm. Additionally, microstructural parameters such as lattice strain, dislocation density, and elastic strain energy density were assessed using Williamson–Hall analysis and the size–strain plot method. The corresponding Energy dispersive X-ray spectroscopy confirms no extra elements appears and successful formation of ZnO-NPS. Transmission electron microscopy (TE-M) revealed that nanoparticles have an almost spherical morphology with an average diameter of about 20.75 ± 3.99 nm. This value closely matches the value obtained from the XR-D analysis. The optical band gap derived from Tauc plots based on UVVIS absorption analysis was found to be approximately 3.28 eV. Photoluminescence emission (PL-E) spectral deconvolution, revealed four emission bands centered at 399.87, 430.47, 544.10, and 586.09 nm. Overall, this study presents a sustainable approach to the synthesis of ZnO-NPS highlighting their prospective applications in biomedical fields and solar energy conversion.

Keywords: ZnO-NPS, Solution combustion, Aloe-vera, Williamson-Hall model and Size–strain model



Graphical abstract

1. Introduction

Nanotechnology has become a cornerstone of materials science, enabling the development of advanced materials with novel properties at the nanoscale. Among various nanomaterials, Zinc oxide nanoparticles (ZnO-NPS) have garnered significant interest owing to their versatile applications across a wide spectrum of fields [1]. The common phase of ZnO is the wurtzite hexagonal phase, which is stable at ambient conditions [2]. It is broadly employed in range of industrial products including ceramics, glass, cement, paints [3, 4], pigments, ointments and medical adhesives [5]. In addition, it is categorized as wide band gap, around 3.2 eV, n-type II-VI semi-conductor material. Moreover, its nanostructured dimension is attractive since it has fascinating optical, structural and electrical properties, primarily in piezoelectric semiconducting properties, solar cell, photocatalysts, sensing and bio-sensing applications [6]. Furthermore, it is a nontoxic material, which means that it has many applications in the food industry, and bio-medication such as first-aid tapes and as an active antimicrobial agent [7]. Indeed, variety of chemical and physical methods are being employed to synthesize ZnO-NPS like sol gel [8], chemical vapor condensation, hydrothermal, microemulsion [9]. In addition, the combustion technique employs inexpensive precursors and does not require sophisticated equipment, making it highly cost-effective. Due to its exothermic and self-sustaining nature, nanoparticle synthesis can be completed within a short duration. Additionally, the technique is simple and easy to implement, enabling uncomplicated scalability from laboratory-scale to industrial-scale production [10]. Till now, several chemical fuels such as urea ($\text{CH}_4\text{N}_2\text{O}$), glycine ($\text{C}_2\text{H}_5\text{NO}_2$), carbonylhydrazide ($\text{OC}(\text{N}_2\text{H}_3)_2$) and citric acid ($\text{C}_6\text{H}_8\text{O}_7$) have been used for the combustion synthesis of metal oxides [16-17]. Currently, the majority of studies of the preparation of M-O-X NPs are concentrated on the employing natural, environmentally friendly materials. Of these, various plants are emerging as an alternative

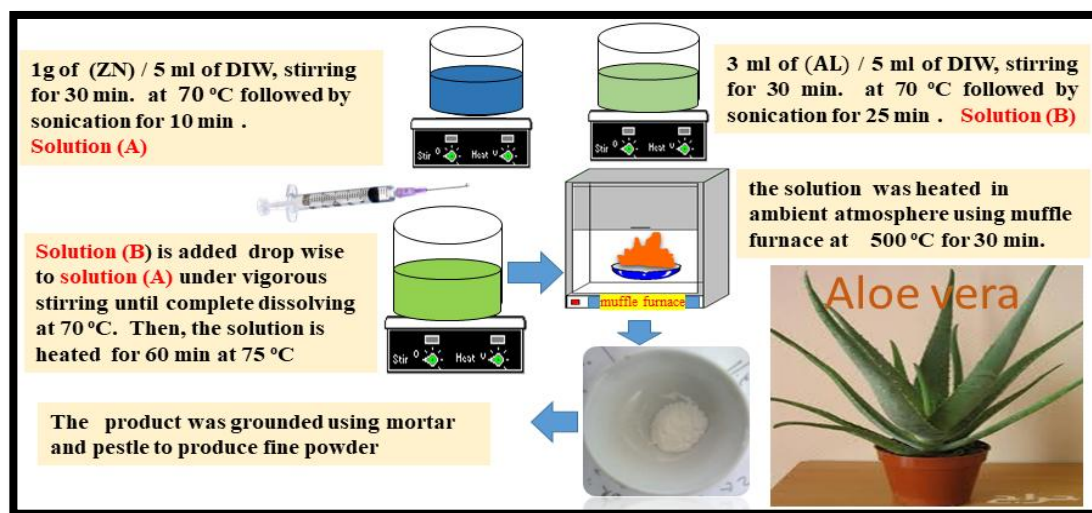
source of chemicals, which are considered the most promising candidates because of their potential to bio-synthesizing NPs on a mass scale[11]. They are readily accessible, broadly distributed, safe to handle and less expensive. On the other hand, it has been used by various researchers as eco-friendly stabilizing agent. In addition, plant extract-mediated synthesis offers a simple, one-step procedure for producing stable nanoparticles without the need for external reducing agents [12]. This green synthesis approach presents significant advantages over microbial methods, including easier scalability, reduced biohazard risk, and a more straightforward process without the need to maintain complex instruments [13]. The proposed synthesis method differs from conventional techniques such as physical vapor deposition, hydrothermal synthesis, spray pyrolysis, microwave-assisted sol-gel and others. Which require a greater quantity of chemical reagents to initiate and sustain the reaction. In addition, release non-reactive materials and some of them give off toxic gases as a result of chemical reactions[13, 14]. Of the numerous techniques used for synthesis NPs, solution combustion technique (SCT) stands out due to its rapid reaction rate, energy efficiency. ,Additionally ability to provide isotropic and controllable nanostructures oxides with high porosity[15, 16] . Over the past few years, a variety of biomaterials have been utilized for the synthesis of metal oxide NPs, including gum arabic[17], green tea [18] and aloe vera (Aloe Barbadensis Mille). Among these, Aloe vera is a perennial succulent herb from the Liliaceae family. It has long been reported to possess skin-protective, immunomodulatory, anti-inflammatory, and wound-healing properties[19]. Herein, we report the synthesis of ZnO-NPS through a cost effective and efficient SCT. Zinc nitrate hexahydrate was employed as the zinc ion source, while the transparent latex extracted from Aloe vera leaves served as the organic fuel. The synthesis was carried out in the absence of any supplementary chemical or natural additives. Mechanical and structural parameters were derived using the analysis of XR-D patterns by different models. Optical analyses were performed using Ultraviolet-Visible (UVVIS) spectroscopy and photoluminescence emission (PL-E) spectroscopy.

2. Experimental Section

2.1 The protocol of Synthesis

Zinc-nitrate-hexahydrate (ZnN) 98% was purchased from Merck Co. Ltd. and used without any more refining. Fresh Aloe vera leaves (Aloe barbadensis Miller, designated as AVL) were harvested from the garden of Al-Azhar University in Gaza in March and carefully rinsed with distilled water several times to eliminate the dust or any surface contaminants. Then, each AVL leaf was cut into ten pieces to facilitate the extraction the desired quantity of fresh latex. About 1000 mg of ZnN was completely dissolved in 5 mL of de-ionized water (DI-W) under vigorous stirring for 30 min at 70 °C followed by ultrasonication for 10 min until fully dissolved until transparent and clear solution was obtained. After that, 3 mL of fresh AL latex was dissolved in 5 mL of DI-W under vigorous stirring at approximately 70 oC followed by ultrasonication for 25 min until completely dissolved. Subsequently, AVL solution was added dropwise to the ZnN solution in a uniform manner. The blended solution was transferred to a300 ml ceramic crucible and then heated on a hot plate magnetic stirrer at 75 oC for about 60 min. Afterwards, the muffle furnace was preheated and upon reaching 500 ± 5 °C, the

crucible was placed in the furnace (surrounding atmosphere) for approximately half an hour. During the combustion process, a flame persisted for approximately 33 s. Additionally, some of chemical gases were released during the reaction. The temperature of the muffle furnace increased 4-7 °C due to the amount of heat emitted and flame during the reaction. The crucible was left in the furnace for 5 hours until it cooled down to room temp. The resulting fluffy white powder obtained. The powder was gently grounded using mortar and pestle for 14 minutes. Scheme 1. Demonstrates comprehensive details of the synthesis protocol.



Scheme 1. Illustration of eco-friendly combustion synthesis of ZnO-NPS. using Aloe Vera latex.

2.2 Instrumentation Techniques

X-ray diffraction (XR-D) characterization was done using a Bruker D8 advance diffractometer with Cu-K α radiation ($\lambda = 0.1540$ nm). The instrument was operated in continuous scan mode over a 2θ range of $18^\circ - 75^\circ$. Where a step size of about 0.015° . The resulting diffraction patterns were used to estimate the crystallite size, confirm phase purity and calculating some structural properties. The absorption test was performed using the double beam (Shimadzu UV-1601 PC) UVVIS spectrometer in the wavelength range of 355–820 nm. The analysis was conducted at room temperature (around 28°C) in surrounding environment. The photoluminescence emission (PL-E) spectrum was carried out under the same condition as UVVIS spectrum. The photoluminescence emission (PL-E) spectrum was collected with the spectro-fluorimeter model SPF-200 (UK, Biotech -Eng.-Management Co.). The spectrum data were taken within the range from 355 nm to 610 nm. The morphological properties and average particle size were examined using (JEOL-JEM2100) advanced transmission electron microscopy at high resolution (TEMHR), worked with 200 kV.

3. Results and Discussion

3.1 Powder X-RD analysis

Fig. 1 shows the X-RD patterns of as-synthesized ZnO-NPS displaying diffraction peak positions corresponding to specific Miller index planes. These diffraction peaks confirm the formation of the hexagonal wurtzite phase of ZnO (DB card No. 230013, space group P63mc, No.186). As seen, no additional peaks, confirming their high purity and the creation of a single-phase polycrystalline ZnO structure with multiple orientations. The most intense diffraction peak appears at 36.2°, corresponding to the (101) Miller index plane, which dominates over the other peaks, in agreement with reference [20, 21].

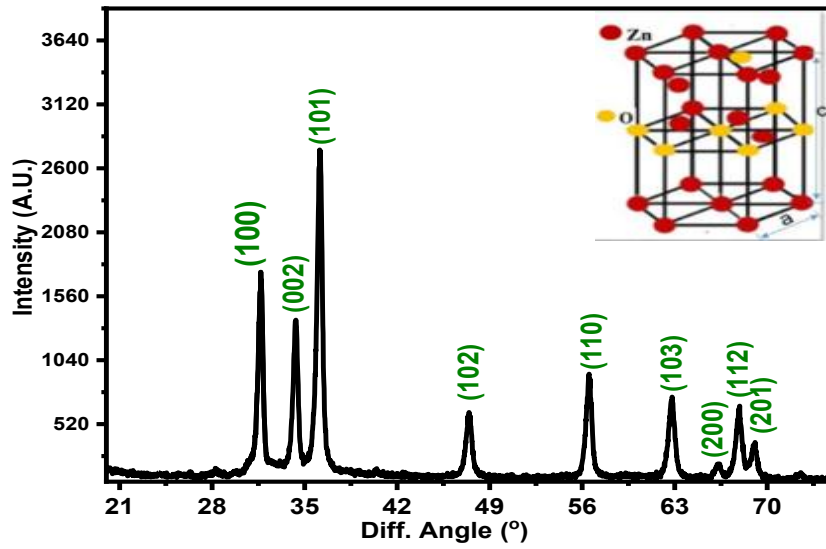


Fig. 1. XR-D patterns of ZnO-NPS. The inset represents the wurtzite- hexagonal ZnO crystal .

However, the intense diffraction peaks indicates the good crystallinity of the synthesized ZnO-NPS[22, 23]. As designated by Bragg's law

$$2 d \sin(\phi) - m\lambda = 0 \quad (1)$$

Where, m represents the order of diffraction and normally equal to 1, λ is the wavelength of the x-ray beam, d is the lattice spacing. In case of hexagonal structure (ZnO case), is governed by a , c lattice constants as well as the Miller indices (h , k and l) by the following equation[24].

$$d_{hkl} = (\sqrt{3}ac)^2 \left[\frac{1}{4c^2(h^2 + hk + k^2) + (\sqrt{3}al)^2} \right]^{0.5} \quad (2)$$

Usually, when the value of m equal one we can get the following equation [25].

$$\left[\left(\frac{2a}{\lambda} \right)^2 \sin^2(\phi) \right] = \left[\frac{4}{3}(h^2 + hk + k^2) + \left(\frac{a}{c}l \right)^2 \right] \quad (3)$$

Suppose that, for h,k,l indices equal 1, 0 and 0 respectively, the parameter (a) can easily be calculated. In this case the equation involves only the wavelength and the angle, as shown in eqn. (4) [26].

$$a = 0.577 \left(\frac{\lambda}{\sin(\phi_{100})} \right) \quad (4)$$

For h and k are equal to zero and l=2, the lattice constant c for the plane (0,0,2) can be calculated using succeeding eqn.[26].

$$c = \lambda(\sin(\phi_{002}))^{-1} \quad (5)$$

Using the lattice parameters a and c of the hexagonal crystal structure, the volume unit cell ($\hat{u}$) can be estimated easily using the following eqn.[24].

$$\hat{u} = 0.866 c * a^2 \quad (6)$$

The calculated value of (a) and (c) are about 0.3263 nm and 0.5223 nm subsequently. Moreover, the computed (ca^{-1}) ratio of 1.600 exhibits an excellent agreement with the reported value of 1.63 corresponding to the ideal case of ZnO in the same crystallography phase [27]. The extracted value of the unit cell volume was to be about 48.152 Å. Additionally, For ZnO wurtzite structure, the positional parameter (q) of O in ZnO (fraction along c-axis), which describes the internal coordinate along the c-axis for the oxygen atoms, can be calculated from the next eqn. [25].

$$q = \frac{1}{3}(ca^{-1})^2 + \frac{1}{4} \quad (7)$$

The Zn–O bond length (I) which is the distance of the neighboring atoms can be expressed as as[25]

$$I = \sqrt{\left(\left(\frac{a}{\sqrt{3}} \right)^2 + c^2(0.5 - q)^2 \right)} \quad (8)$$

The obtained values of I were closely aligned, averaging around 1.977 (Å), which agrees well with the values documented by Amad et al. and Seetawan et al.[1, 28]. On the other hand, the distortion parameter (ξ) depends strongly on the crystallite dimensions can be easily calculated using next equation:

$$\xi = \frac{(a\sqrt{c})^2 - (a\sqrt{c})^2}{(a\sqrt{c})^2} \quad (9)$$

Where, a and c are equal to 0.325 nm and 0.521 nm respectively. Besides that, atomic packing factor (A) is a quantifies the fraction of volume occupied by atoms in a unit cell. It is a dimensionless quantity determined by atomic radii and the nature of interatomic bonding [29, 30].

$$A = \frac{N_{particle} * V_{particle}}{V_{unit cell}} \quad (10)$$

For ZnO crystal, Eq. (10) becomes [29, 30]

$$A = \left(\frac{2\pi}{3\sqrt{3}} \right) (c/a)^{-1} \quad (11)$$

where a and c indicates the measured lattice constants. For bulk hexagonal ZnO, the reported value of A is around 74%. On the other hand, the calculated value for ZnO-NPS is roughly 75.52%. It means that, packing factor in nanocrystals is greater than that of in bulk materials case. This value closely matches the results reported by Adhana et al. [30]. Some of structural parameters of ZnO-NPS, which extracted using the X-RD broadening have been listed in Table 1.

Peaks (hkl)	(2 ϕ)	FWHM	$D_{AVG.}$ (nm)	c^*a^{-1}	q	Γ (Å)	$\bar{U}$ (Å)	ξ	A %
(100)	31.662	0.432							
(002)	34.314	0.466	18.24	1.600	0.380	1.977	48.152	0.011	75.520
(101)	36.139	0.470							

3.1.1 Debye-Scherrer method

The Bragg peak broadening observed in the X-RD pattern arises from both sample-related and instrumental contributions. The instrumental broadening-corrected value (β_{hkl}) for the ZnO peak was calculated using the following expression[31].

$$\beta_{hkl} = ([(\beta_{\text{measurement}})^2 - (\beta_{\text{instrument}})^2])^{0.5} \quad (12)$$

The average crystals volume ($D_{AVG.}$) was considered using the Debye-Scherrer formula, a widely accepted method for size estimation from X-RD data [32].

$$D_{AVG.} = \left(K\lambda / \beta_{hkl} \right) \cos(\phi) \quad (13)$$

In this equation, K denotes the shape factor, typically valued at ~ 0.9 for semi spherical crystallites, λ wavelength of the X-RD beam, ϕ represents the Bragg diffraction angle, and β_{hkl} corresponds to the full width at half maximum (F-W-H-M) of the diffraction peak. The average crystallite size $D_{AVG.}$ was estimated using the β_{hkl} values from the most intense X-RD reflections, specifically those indexed to the (100), (002), and (101) planes, yielding a size of approximately 18nm.

3.1.2 Williamson-Hall Models

Scherrer model proposed that the peak broadening (β_{hkl}) is only due to crystallite size; strain distortions effects are ignored. So, it does not consider lattice strain or other contributing factors to peak broadening. However, in real materials especially nano-materials, peak broadening can also result from micro-strain, which arises due to lattice stress, imperfections or dislocations [33]. On the other hand, the Williamson-Hall (W-H) models was proposed as an extension of the Scherrer model to account for both crystallite size and lattice strain contributions to peak broadening of size. Consequently, analysis of peak broadening utilized for estimating $D_{AVG.}$, strain (ϵ) and some of other mechanical-structure parameters [25, 33]. Accordingly, the total peak broadening β_{hkl} can be expressed [34-37].

$$\beta_{hkl} = \beta_{sh} + \beta_{st} \quad (14)$$

Substituting the $\beta_{Sh} = K \lambda / D_{AVG} \cos(\phi)$ and $\beta_{St} = 4\epsilon / \tan(\phi)$ into Eq. (14), consequently repositioning it gives

$$\beta_{hkl} \cos(\phi) = \left[(4\epsilon \sin(\phi)) + K \left(\frac{\lambda}{D_{AVG}} \right) \right] \quad (15)$$

Equation (15) represents the Uniform Deformation Model (U-D-M) within the framework of the Williamson–Hall (W–H) model, which suppose that the micro-strain are an equal distribution of micro-strain in every crystallographic orientation [31]. The U-D-M analysis for ZnO-NPS is presented in Fig. 2. In this approach, the strain is determined from the slope of the linear fit, while the D_{AVG} is obtained from the y-intercept. The calculated values of ϵ and D_{AVG} based on the U-D-M are listed in Table 2.

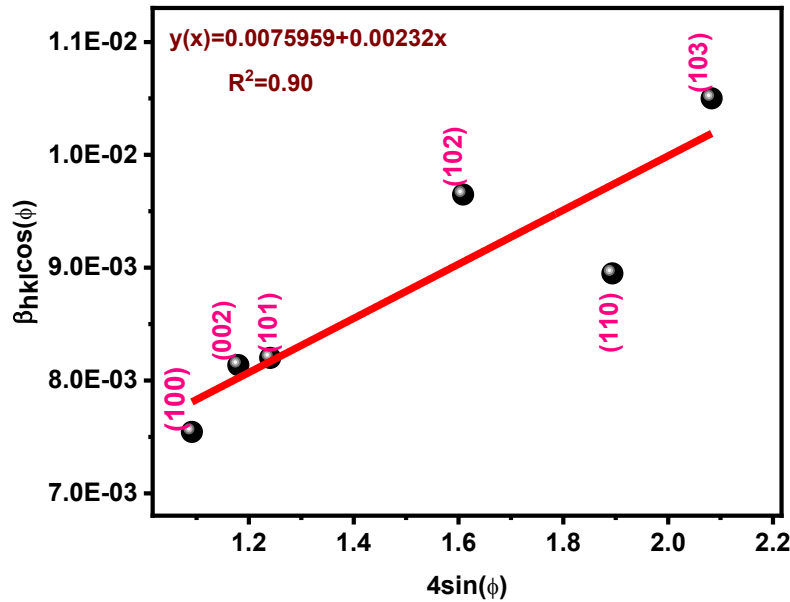


Fig. 2. Uniform deformation model plot for ZnO-NPS

While the assumptions of homogeneity and isotropy are commonly used in modelling crystalline materials, real crystals often exhibit deviations due to structural imperfections, anisotropy, and compositional inhomogeneities. To account for anisotropic strain effects, the Uniform Stress Deformation Model (U-S-D-M) was employed. This model assumes a uniform distribution of lattice deformation stress across all crystallographic directions, while considering the presence of relatively small anisotropic micro-strain within the crystal lattice[25]. As a result, stress and strain are linearly proportional, consistent with Hooke's Law. $\sigma = \epsilon * Y_{hkl}$ where, Y_{hkl} is Young's modulus and σ is the uniform deformation stress. By applying Hooke's law approximation to Equation (15), the following eqn. is obtained[38, 39]:

$$\beta_{hkl} \cos(\phi) = (4\sigma \sin(\phi) / Y_{hkl}) + (K \lambda / D_{AVG}) \quad (16)$$

In our case, Y_{hkl} reported by Jieh et al. [38, 39]. The calculated value of D_{AVG} and σ by U-S-D-M was about 18.46 nm and σ around 71.31 MPa. Respectively. Such obtained value is agreed well with that was reported in refs. [40, 41]. Fig. 3 illustrates the plotting of $(\beta_{hkl}\cos(\phi))$ versus $(4\sin(\phi)/Y_{hkl})$. The uniform deformation ϵ as well as σ can be calibrated from slope whereas, D_{AVG} can be assessed from the y-intercept. U-S-D-M estimated data of D_{AVG} , ϵ and σ are itemized in Table 2.

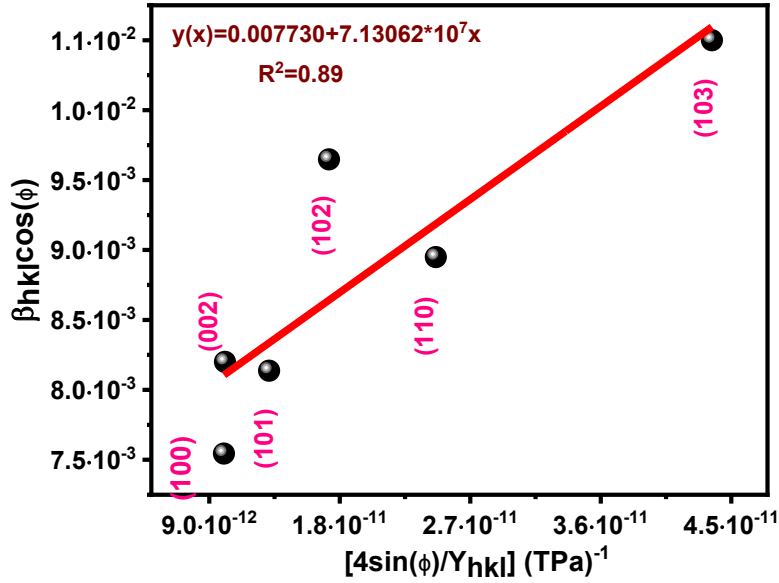


Fig. 3. Uniform stress deformation model plot for ZnO-NPS

In real polycrystalline systems, the presence of dislocations, various defects, and particle agglomerations introduces structural imperfections that invalidate the assumptions of isotropy and uniform stress-strain behavior. Subsequently, the isotropic assumption underlying the U-D-M and the linear stress-strain relationship assumed in the U-S-D-M may not be applicable in many cases, including the present investigation[38]. Consequently, the Uniform Deformation Energy Density Model (U-D-E-D-M) has been introduced. This model incorporates the concept of deformation energy density, which accounts for strain anisotropy by introducing a directionally dependent strain component. According to Hooke's Law, the deformation energy density (u) is related to strain by the following equation [42].

$$2u/(\epsilon)^2 = Y_{hkl} \quad (17)$$

As a result, the Eq. (15) can be adapted to be

$$\beta_{hkl} \cos(\phi) = 4 \sin(\phi) * \sqrt{2u/Y_{hkl}} + \lambda(K/D_{AVG}) \quad (18)$$

Fig. 4 displays the plot of $4\sin(\phi)(2/Y_{hkl})^{0.5}$ vs $\beta_{hkl} \cos(\phi)$. The value of u was extracted from slope of the linear fit. Then, D_{AVG} value can be calculated from y-intercept. All the calculated values representing mechanical and structural values are listed in Table 2. The close agreement among the values derived from different Williamson–Hall (W–H) models indicates that these

approaches are valid and reliable for estimating structural parameters, such as the average crystallite size, and other mechanical parameters for ZnO. This consistency reinforces the suitability of the W–H method for analyzing nanoscale crystalline materials, despite the presence of anisotropic strain.

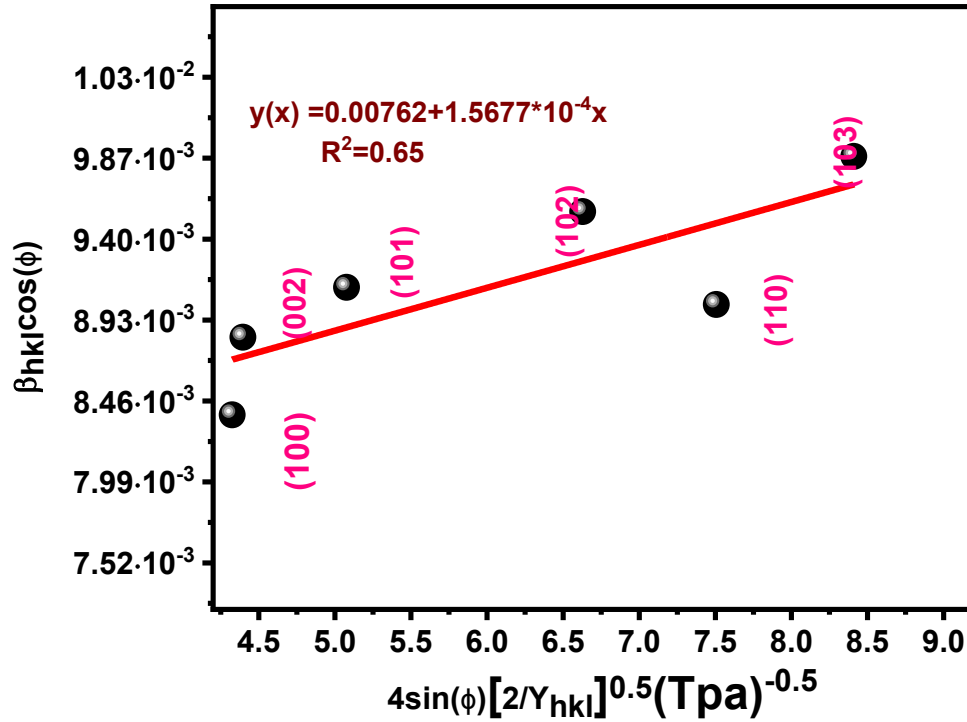


Fig. 4. Uniform deformation energy density model plot for ZnO-NPS.

3.1.3 Size-Strain Model

The Size–Strain Plot ($\hat{S}$ – $\hat{S}$) model is an alternative approach to the Williamson–Hall model for analyzing X-ray diffraction (X-RD) peak broadening caused by both crystallite size and lattice strain. Unlike linear models that equally weight all diffraction peaks, the $\hat{S}$ – $\hat{S}$ model can be expressed as the overall peak broadening based on the sum of Gaussian and Lorentzian Functions[38]. This model places greater emphasis on data from high-angle peaks, which are more sensitive to strain, resulting in improved reliability in estimating microstructural parameters, particularly for anisotropic or defect-rich nanomaterials such as ZnO-NPS. Allowing a more accurate separation of the contributions from crystallite size and micro-strain. Fig. 5 illustrates $\{ (d_{hkl} \beta_{hkl} \cos(\phi))^2 \}$ on the y-axis against $\{ (d_{hkl}^2 \beta_{hkl} \cos(\phi)) \}$, on the x-axis [25, 43] as depicted in Eq.(19).

$$(d_{hkl} \beta_{hkl} \cos(\phi))^2 = K(\lambda / D_{AVG.}) (d_{hkl}^2 \beta_{hkl} \cos(\phi)) + (\lambda/2)^2 \quad (19)$$

D_{AVG} . is found from slope linearly fitted data and root of the y-intercept gives $\mathcal{Z}$. The foremost lattice parameters (D_{AVG} , $\mathcal{Z}$, σ and u) estimated from $\hat{S}$ - $\hat{S}$ models are tabulated in Table 2

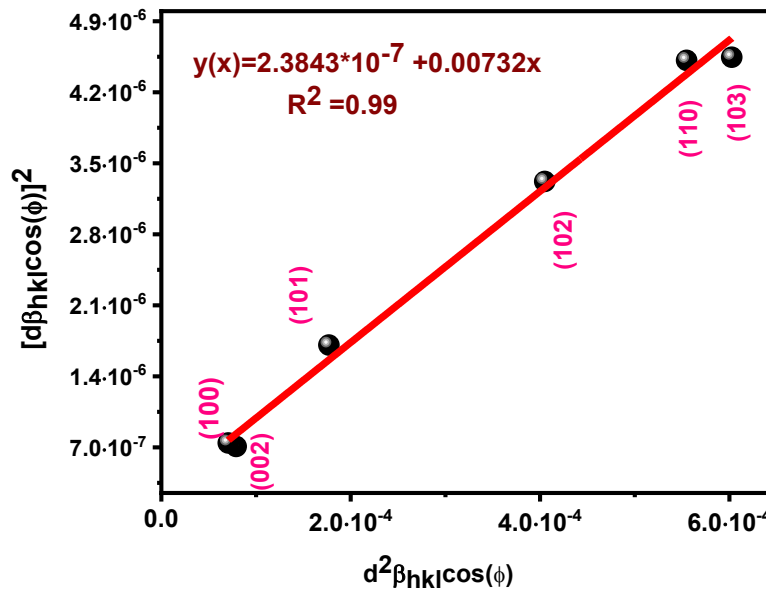


Fig. 5. Size-strain-plot of ZnO-NPS.

Table 2 Summarized of microstructural parameters of ZnO crystallite

Williamson-Hall Model								Size-strain Model			
UDM				U-S-D-M				$\hat{S}$ - $\hat{S}$			
$\mathcal{Z}$	D_{AVG}	$\mathcal{Z}$	σ	D_{AVG}	$\mathcal{Z}$	Σ	u	D_{AVG}	σ	U	D_{AVG}
$\times 10^{-3}$	(nm)	$\times 10^{-3}$	(MPa)	(nm)	$\times 10^{-3}$	(MPa)	(kJm^{-3})	(nm)	(MPa)	(kJm^{-3})	(nm)
2.32	18.60	0.82	71.31	18.9	0.98	88.02	31.54	18.20	85.25	41.92	18.98
3											

3.2 Energy dispersive X-ray spectroscopy (EDX-S)

The particle distribution, and elemental composition of the synthesized (ZnO-NPS) were examined using Scanning Electron Microscopy (SE-M) equipped with Energy-Dispersive X-ray Spectroscopy (EDX-S), as shown in Fig. 6. The SE-M micrograph illustrated porous-like network consisting of aggregated spherical NPS. The tiny NPS creates a rough surface texture with interparticle voids, through the solution combustion synthesis technique due to the release of gases during the exothermic reaction. The corresponding EDX-S (Figure 6, left) confirms

no extra elements appears and successful formation of ZnO-NPS. The spectrum displays major characteristic peaks corresponding exclusively to Zinc (Zn) and Oxygen (O). The absence of extraneous peaks verifies that the green combustion process using *Aloe vera* latex yields pure ZnO-NPS free from unreacted precursor. This observation supports the high purity of the material and is in good agreement with the X-RD results. The quantitative EDX-S analysis revealed that Zn and O constitute 77.22% and ~22.78% of the sample weight, respectively. These values indicate a slightly oxygen-rich composition compared to the ideal stoichiometry of ZnO (80.34 % Zn and 19.66% O) by weight. Structurally, this oxygen enrichment reduces oxygen vacancies (V_o) and enhances the formation of zinc vacancies (V_{zn}) and interstitial oxygen (O_i) in the lattice. As shown in the PL spectra (Fig. 9) in the next section. The lower concentration of (V_o) suppresses the typical green emission, while the high density of (V_{zn}) defects enhances the violet-blue emission band.

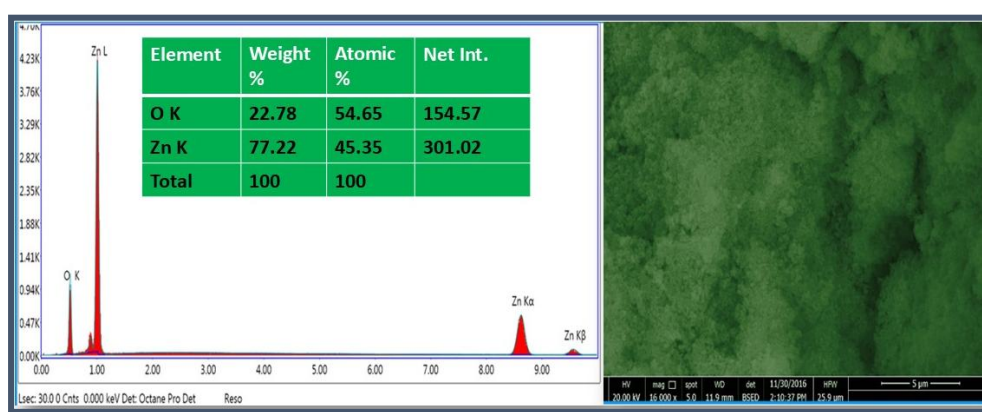


Fig. 6. EDX-S and SEM image of pure ZnO NPS.

3.3 Transmission electron microscopy (TE-M) analysis

Transmission electron microscopy (TE-M) was employed to investigate the morphology, particle size, and degree of agglomeration of the synthesized ZnO-NPS. As shown in Fig. 7(a), the particles exhibit a nearly spherical morphology with a noticeable intermediate degree of agglomeration. The particle-size distribution was obtained by analyzing the TE-M micrograph and constructing the histogram shown in Fig. 7(b). The average particle size was estimated to be approximately 20.75 ± 3.99 nm. This value is reasonably close to the average crystallite size obtained from the XRD analysis. The difference between the TE-M particle size and the XRD crystallite size may be attributed to the fact that an individual particle can consist of one or more crystallites.

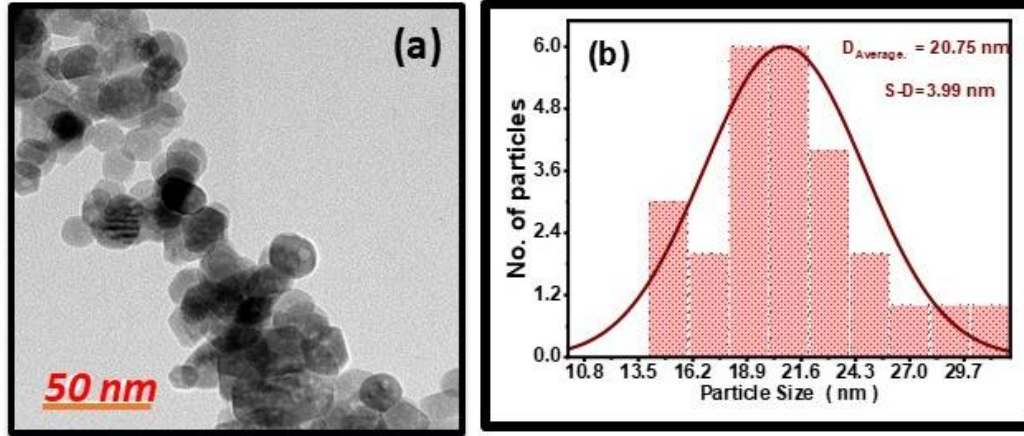


Fig. 7. (a) TE-M micrograph and (b) Particle size histogram of prepared pure ZnO-NPS.

3.4 Optical analysis

3.4.1 UVVIS absorption spectroscopy

UVVIS spectroscopic absorption was employed to examine the optical absorption behavior of the prepared material across different wavelengths. In addition, the optical technique was employed to estimate the optical band gap using a simple and straightforward approach. For the UVVIS analysis, a suitable amount of the synthesized ZnO was dissolved in absolute ethanol for 18 minutes under stirring, and then sonicated for an additional 20 minutes to get a uniform cloudy suspension. Fig. 8 shows the typical UVVIS absorption spectrum of the ZnO-NPS in the range of 350 to 820 nm. Basically, the UV absorption edge is due to the electronic transitions from the filled valence bands (V-B) to vacant conduction bands (C-B). The maximum absorption edge ($\lambda_{\max}$) was observed at approximately 371.3 nm, which is blue shifted to the lower value compared to the bulk ZnO. This behavior can be attributed to quantum confinements effect[44]. Additionally, by applying the Tauc-Davis and Mott equation, the optical energy gap (E_g) can be easily detected from the absorption spectrum [45, 46].

$$\beta hf = \tilde{A}(hf - E_g)^k \quad (20)$$

Where, $\tilde{A}$ is the absorption constant, h is the Planck's constant, f is the frequency of photon, and E_g is the optical energy gap. In our case, electronic transitions are direct allowed electronic transitions so, $k = 0.5$ [32]. The E_g can be determined easily by plotting $(\beta hf)^2$ versus photon energy (hf) and extrapolation of the linear portion of the curve to $(\beta hf)^2 = \text{zero}$. The inset of Fig. 8 shows that the determined E_g was around 3.28 eV. These findings are consistent with our previous study, in which urea was utilized as a fuel in the combustion synthesis technique [10].

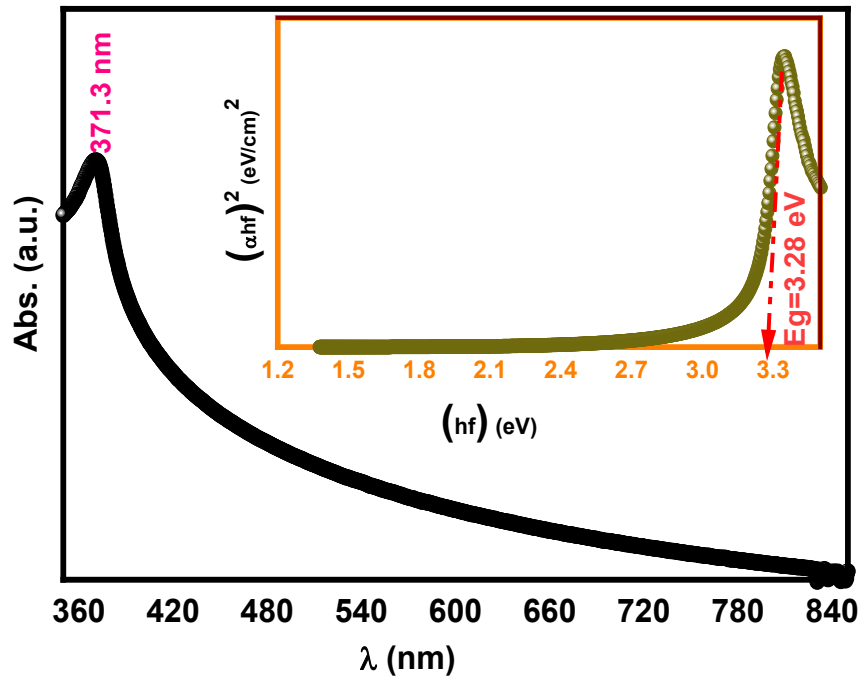


Fig. 8. Typical (UVVIS) of ZnO-NPS The inset represents the zoom of the Tauc plot region (golden color).

3.4.2 Photoluminescence emission spectroscopy

Photo-luminescence emission (PL-E) spectroscopy is a powerful technique used to probe the electronic structure and defects state of a material. The PL emissions spectrum was recorded upon excitation of (0.1mg/mL) ethanolic suspension of ZnO-NPS, with The excitation energy corresponding to a wavelength of 253 nm. As illustrated in Fig. 9, the PL-E spectrum was deconvoluted into four primary peaks using Gaussian multi-peak curve-fitting. This analysis helps identify the contributing emission components and provides a clearer interpretation of the spectral features. The first emission peak (Peak I), centered at 399.87 nm (3.11 eV), corresponds to the Near-Band-Edge (NBE) emission in the UVVIS region, arising from the direct radiative recombination of free excitons. Peak I exhibits a sharp profile with high relative intensity [23]. A pronounced and broad emission centered around 430.47 nm (2.88 eV) was observed as the second peak (peak II). This violet -blue is due to electron transition from shallow doner states near the conduction band to deep acceptor levels created by zinc vacancies (V_{Zn}) [47, 48]. An increased oxygen weight percentage in the ZnO leads to a higher probability of zinc vacancy formation. Consequently, this resulted in the enhanced broadening and intensity of the second peak, which is further corroborated by prior EDX analysis. The high intensity of the peak is attributed to the large number of electronic transitions confined within a narrow wavelength range.

The third peak (Peak III), is narrow weak peak centered around 544.10 nm, is attributed to green defect emission, conventionally associated with oxygen vacancies (V_o) [48, 49]. A yellow-orange emission was observed in the fourth peak (Peak IV), centered around 586.09 nm (2.10 eV). Excess oxygen in the sample preferentially accumulates at grain boundaries and nanostructure surfaces as interstitial oxygen (O_i) or adsorbed oxygen species [23, 49]. This creates trap states that yield lower-energy radiative transitions around 2.10 eV. Fig. 10 illustrates the emission mechanism generated as a result of ZnO-NP excitation. In addition, Table 3 displays the parameters extracted from the fitting of pl emission of synthesized ZnO NPS.

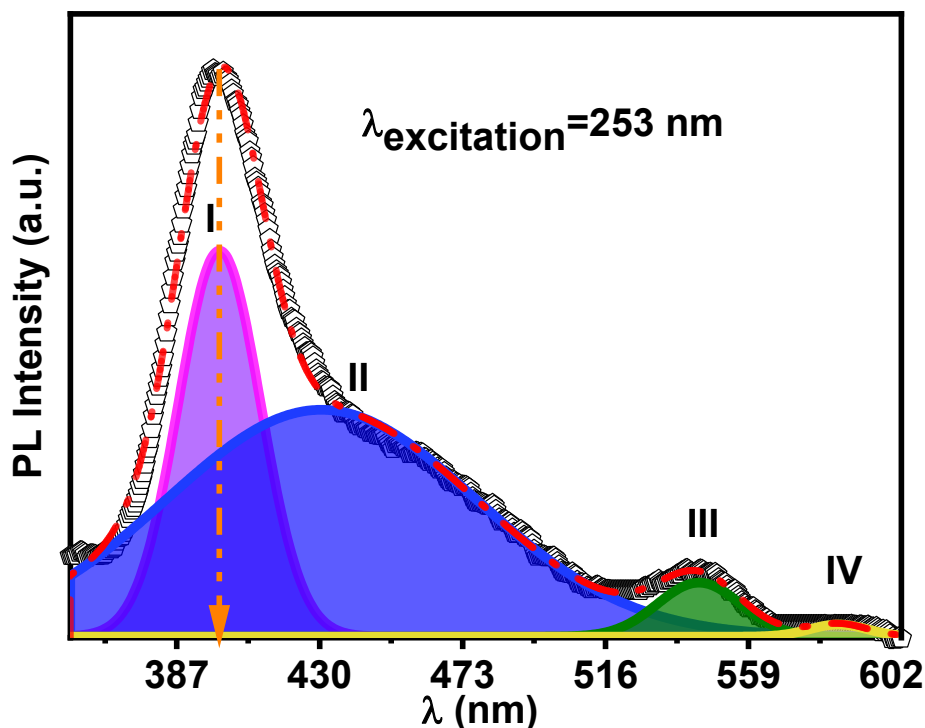


Fig. 9. The luminescence emission spectrum and deconvoluted peaks for pure ZnO-NPS.

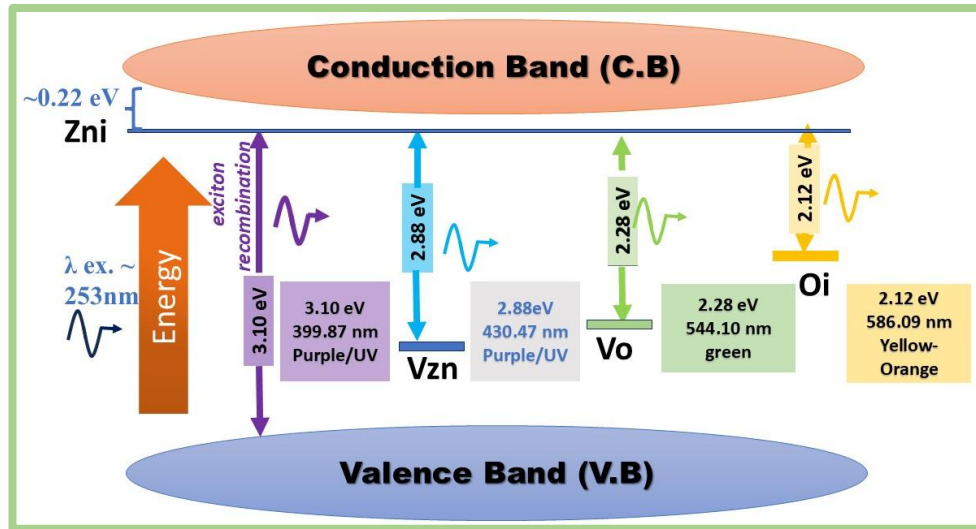


Fig. 10 Energy level diagram of emissions resulting from the excitation of ZnO-NPS .

Table 3. PL emission peak characteristics of synthesized ZnO NPS.

Peak No.	Peak position (nm)	Energy (eV)	Relative intensity (a.u.)	FWHM (nm)	Integrated area	Normalized area (%)
I	399.87	3.10	885	29.08 ± 0.22	26,934.43 ± 287.42	29.61
II	430.47	2.88	526	109.53 ± 0.74	59,628.39 ± 492.49	65.53
III	544.10	2.28	134	29.40 ± 1.30	3,809.99 ± 155.38	4.19
IV	586.09	2.12	51	20.49 ± 4.53	597.77 ± 119.59	0.66

4 Conclusions

ZnO nanoparticles were successfully synthesized through an Aloe vera latex-assisted solution-combustion method. X-ray diffraction confirmed the formation of a single-phase multi-crystalline hexagonal wurtzite structure, with an average crystallite size of approximately 18 nm. The close agreement among the Debye–Scherrer, Williamson–Hall, and size–strain models supports the reliability of the structural analysis. Transmission electron microscopy further revealed nearly spherical particles with an average size of about 20.75±3.99 nm. ED-X analysis detected only zinc and oxygen, indicating the absence of detectable elemental impurities. The measured composition of 77.22 wt.% Zn and 22.78 wt.% O suggests a slight oxygen excess relative to stoichiometric ZnO. The optical measurements showed an absorption edge near 371.3 nm and a direct band gap of approximately 3.28 eV. Deconvolution of the PL spectrum identified four emission bands at 399.87, 430.47, 544.10, and 586.09 nm. The broad blue band centered at 430.47 nm was the principal emission component by integrated area, contributing 65.53%, while the near-UV/violet band accounted for 29.61%. The much smaller contributions of the yellowish-green and yellow-orange bands, 4.19% and 0.66%, respectively, indicate that these visible defect-related emissions were comparatively weak.

Acknowledgment

The authors would like to acknowledge the support of University Littoral Côte d'Opale (ULCO), University of Picardie Jules Verne (UPJV) and the College de France through the PAUSE program, which hosted Hussam Musleh and Naji Aldahoudi

Author Contributions

Hussam Musleh developed the methodology, curated the data, created the figures, and wrote the initial manuscript. Abdelylah Daoudi supervised the project, offered conceptual guidance, analyzed data, and helped revise the paper. Samy Mansy ran the calculations, contributed to the methodology, and validated the findings. Naji Aldahoudi assisted with formal analysis, results validation, scientific discussion, and editing. Abdelilah Lahmar helped interpret the data, contributed to theoretical discussions, and edited the draft. Yahia Boussoualem carried out formal analysis and participated in revising the manuscript. Khaoula Ferchichi performed formal analysis and validated the computational results. Finally, all authors reviewed, refined, and approved the final manuscript.

Funding

This work was supported by the University Littoral Côte d'Opale (ULCO), University of Picardie Jules Verne (UPJV) and the College de France through the PAUSE program.

Data availability

All data generated or analyzed during this study are included in this published article. Additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest

The authors declare no competing interests.

Ethical approval

This article does not require ethical approval.

References

1. Abdulqodus, A.N., et al., *Green synthesis of ZnO nanoparticles: effect of pH on morphology and photocatalytic degradation efficiency*. Applied Physics A, 2025. **131**(9): p. 720.
2. Ashrafi, A. and C. Jagadish, *Review of zincblende ZnO: Stability of metastable ZnO phases*. Journal of Applied Physics, 2007. **102**(7): p. 12.
3. Casa, M., et al., *Synthesis and characterization of water stable ZnO quantum dots based-sensor for nitro-organic compounds*. Chemical Engineering Transactions, 2016. **47**: p. 7-12.
4. Zayed, H., et al., *Synthesis of Zinc Oxide nanoparticles at different aging time for low cost Dye Sensitized Solar Cells*. Journal of Scientific Research in Science, 2018. **34**(part1): p. 275-286.

5. Verbič, A., M. Gorjanc, and B. Simončič, *Zinc Oxide for Functional Textile Coatings: Recent Advances*. Coatings, 2019. **9**(9): p. 550.
6. Musleh, H., et al. *Synthesis and characterization of ZnO nanoparticles using sol gel technique for dye sensitized solar cells applications*. in *Journal of Physics: Conference Series*. 2019. IOP Publishing.
7. Vasilache, V., et al. *Nanoparticles applications for improving the food safety and food processing*. in *7th International Conference on Materials Science and Engineering–BRAMAT Braşov, ebruary*. 2011.
8. Musleh, H., et al., *Synthesis and Characterization of ZnO Nanoparticles Using Hydrothermal and Sol-Gel Techniques for Dye-Sensitized Solar Cells*. Journal of University of Babylon for Engineering Sciences, 2018. **26**(9): p. 256-267.
9. Hasnidawani, J., et al., *Synthesis of ZnO nanostructures using sol-gel method*. Procedia Chemistry, 2016. **19**: p. 211-216.
10. Shaat, S., et al., *Solution combustion-derived ZnO nanoparticles for photoanode of solar cells*. journal of Materials Science Engineering: B, 2019. **241**: p. 75-81.
11. Ayeshamariam, A., et al., *Biosynthesis of (ZnO–Aloe Vera) nanocomposites and antibacterial/antifungal studies*. J Optoelectron Biomed Mater, 2014. **6**(3): p. 85-99.
12. Raj, L.A., R. Pavithra, and S.K.R. Namasivayam, *Green route synthesis of Highly Stable Zinc Oxide Nanoparticles using Root Extract of Andrographis paniculata and evaluation of their potential activities*. Plant Nano Biology, 2025: p. 100162.
13. Ullah, M.N., et al., *Plant-based synthesis of silver nanoparticles and their characteristic properties*. Bioinspired, Biomimetic and Nanobiomaterials, 2017. **6**(1): p. 20-36.
14. Debalke, A.G., B. Abebe, and H. Ananda Murthy, *Synthesis Techniques for Novel Nanomaterials*, in *Advanced Nanomaterials for Energy Storage Devices*. 2024, Springer. p. 77-98.
15. Kredy, H.M., *The effect of pH, temperature on the green synthesis and biochemical activities of silver nanoparticles from Lawsonia inermis extract*. Journal of Pharmaceutical Sciences and Research, 2018. **10**(8): p. 2022-2026.
16. Mashan, T.T., et al., *A Comprehensive Overview of Co3O4 Nanoparticles: Solution Combustion Synthesis and Potential Applications*. Nanomaterials, 2025. **15**(12): p. 932.
17. Fardood, S.T., et al., *Green synthesis of zinc oxide nanoparticles using arabic gum and photocatalytic degradation of direct blue 129 dye under visible light*. Journal of Materials Science: Materials in Electronics, 2017. **28**(18): p. 13596-13601.
18. Senthilkumar, S. and T. Sivakumar, *Green tea (Camellia sinensis) mediated synthesis of zinc oxide (ZnO) nanoparticles and studies on their antimicrobial activities*. Int J Pharm Pharm Sci, 2014. **6**(6): p. 461-465.
19. Yanikoglu, R.S., et al., *Anti-Inflammatory Potential of Pre-Formulated Aloe vera in Mitigating Allergen-Induced Airway Responses in Mice*. Immunology Letters, 2025: p. 107070.
20. Kumar, V., et al., *Origin of the red emission in zinc oxide nanophosphors*. Materials Letters, 2013. **101**: p. 57-60.
21. Guo, K., *Property of zinc oxide (ZnO) nanostructures potential for biomedical system and its common growth mechanism*. J Appl Biotechnol Bioeng, 2017. **2**(5): p. 197-202.
22. Baviskar, P., A. Ennaoui, and B. Sankapal, *Influence of processing parameters on chemically grown ZnO films with low cost Eosin-Y dye towards efficient dye sensitized solar cell*. Solar Energy, 2014. **105**: p. 445-454.
23. Samy Shaat, H.Z., Hussam Musleh, Nabil Shurrah, Ahmed Issa, Jihad Asad, and N.A. Dahoudi, *Inexpensive organic dyes-sensitized zinc oxide nanoparticles photoanode for solar cells devices*. Journal of Photonics for Energy, 2017. **7**(2): p. 025504-1 025504-15.
24. Kaur, J., et al., *Structural, optical and fluorescence properties of wet chemically synthesized ZnO: Pd 2+ nanocrystals*. International Nano Letters, 2013. **3**(1): p. 4.
25. Bindu, P. and S. Thomas, *Estimation of lattice strain in ZnO nanoparticles: X-ray peak profile analysis*. Journal of Theoretical and Applied Physics, 2014. **8**(4): p. 123-134.

26. Kumar, V. and K.V. Rao, *X-ray peak broadening analysis and optical studies of ZnO nanoparticles derived by surfactant assisted combustion synthesis*. 2013.
27. Lavand, A.B. and Y.S. Malghe, *Synthesis, characterization and visible light photocatalytic activity of nitrogen-doped zinc oxide nanospheres*. Journal of Asian Ceramic Societies, 2015. **3**(3): p. 305-310.
28. Seetawan, U., et al., *Effect of calcinations temperature on crystallography and nanoparticles in ZnO disk*. Materials Sciences and Applications, 2011. **2**(2): p. 1302-1306.
29. Perez, N., *Atomic Structure*, in *Materials Science: Theory and Engineering*. 2024, Springer. p. 1-50.
30. Dhanalakshmi, A., et al., *Structural, morphological, optical and antibacterial activity of rod-shaped zinc oxide and manganese-doped zinc oxide nanoparticles*. Pramana, 2016. **87**(4): p. 57.
31. Prabhu, Y.T., et al., *X-ray analysis by Williamson-Hall and size-strain plot methods of ZnO nanoparticles with fuel variation*. World Journal of Nano Science and Engineering, 2014. **4**(01): p. 21.
32. Raveendra, R., et al., *Synthesis, structural characterization of nano ZnTiO₃ ceramic: An effective azo dye adsorbent and antibacterial agent*. Journal of Asian Ceramic Societies, 2014. **2**(4): p. 357-365.
33. Rajesh Kumar, B. and B. Hymavathi, *X-ray peak profile analysis of solid-state sintered alumina doped zinc oxide ceramics by Williamson–Hall and size-strain plot methods*. Journal of Asian Ceramic Societies, 2017. **5**(2): p. 94-103.
34. Mote, V., Y. Purushotham, and B. Dole, *Williamson-Hall analysis in estimation of lattice strain in nanometer-sized ZnO particles*. Journal of Theoretical and Applied Physics, 2012. **6**(1): p. 1-8.
35. Williamson, G. and W. Hall, *X-ray line broadening from fcc aluminium and wolfram*. Acta metallurgica, 1953. **1**(1): p. 22-31.
36. Ogugua, S.N., et al., *Optical properties and chemical composition analyses of mixed rare earth oxyorthosilicate (R₂SiO₅, R=La, Gd and Y) doped Dy³⁺ phosphors prepared by urea-assisted solution combustion method*. Journal of Physics and Chemistry of Solids, 2015. **83**: p. 109-116.
37. Irfan, H., M. Racik K, and S. Anand, *Microstructural evaluation of CoAl₂O₄ nanoparticles by Williamson–Hall and size–strain plot methods*. Journal of Asian Ceramic Societies, 2018. **6**(1): p. 54-62.
38. Lim, J.S. and F.K. Yam, *Structural parameters of CVD synthesized Ga₂O₃ nanostructures from X-ray diffraction analysis derived by Scherrer, Williamson-Hall, Size-Strain Plot and Halder-Wagner methods—A comparative study*. Physica B: Condensed Matter, 2025. **699**: p. 416798.
39. Venkateswarlu, K., et al., *X-ray peak profile analysis of nanostructured hydroxyapatite and fluorapatite*. International Journal of Bioscience, Biochemistry and Bioinformatics, 2012. **2**(6): p. 389-393.
40. Chenari, H.M., H.F. Moafi, and O. Rezaee, *A study on the microstructural parameters of Zn (1-x) La_xZr_xO nanopowders by X-ray line broadening analysis*. Materials Research, 2016. **19**(3): p. 548-554.
41. Sarma, H. and K. Sarma, *X-ray peak broadening analysis of ZnO nanoparticles derived by precipitation method*. Int. J. Sci. Res. Publ, 2014. **4**(3): p. 1-7.
42. Zak, A.K. and W.A. Majid, *Characterization and X-ray peak broadening analysis in PZT nanoparticles prepared by modified sol–gel method*. Ceramics International, 2010. **36**(6): p. 1905-1910.
43. Tagliente, M. and M. Massaro, *Strain-driven (002) preferred orientation of ZnO nanoparticles in ion-implanted silica*. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 2008. **266**(7): p. 1055-1061.

44. Kundu, T.K., et al., *Optical properties of ZnO nanoparticles prepared by chemical method using poly (vinyl alcohol)(PVA) as capping agent*. International Journal of Soft Computing and Engineering, 2011. **1**: p. 19-24.
45. Suhail, A.M., et al., *Syntheses of ZnO Quantum Dot by Self assembly Method and ZnO Nanorod by Hydrothermal Method*. International Journal of Advanced Technology in Engineering and Science, 2015. **3**(4): p. 10.
46. Shaat, S.K., H.C. Swart, and O.M. Ntwaeaborwa, *Investigation of luminescent properties of CaO. 3SrO. 7Al₂O₄: Tb³⁺, Eu³⁺ excited using different excitation sources*. Journal of Electron Spectroscopy and Related Phenomena, 2014. **197**: p. 72-79.
47. Ahn, C.H., et al., *A comparative analysis of deep level emission in ZnO layers deposited by various methods*. Journal of Applied Physics, 2009. **105**(1).
48. Kumar, V., et al., *Rare earth doped zinc oxide nanophosphor powder: a future material for solid state lighting and solar cells*. Acs Photonics, 2017. **4**(11): p. 2613-2637.
49. Kumar, V., et al., *The role of growth atmosphere on the structural and optical quality of defect free ZnO films for strong ultraviolet emission*. Laser Physics, 2014. **24**: p. 10.