

Synthesis and Characterization of ZnO Nanoparticles with Red Betel Leaf Extract (*Piper crocatum*) as a Capping Agent Using the Sonication Method

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Abstract: The green synthesis of zinc oxide (ZnO) nanoparticles utilizing plant extracts offers an economical, non-toxic, and sustainable alternative to conventional chemical methods. This study comprehensively investigated the structural and optical optimization parameters by evaluating the effects of varying volume ratios of red betel leaf extract (*Piper crocatum*) to 0.1 M ZnSO₄·7H₂O precursor, alongside assessing the impact of alkaline pH variations. The entire synthesis procedure was assisted by ultrasound sonication for 30 minutes to enhance particle homogeneity and effectively prevent premature structural agglomeration. Optimization monitored through UV-Vis spectrophotometry revealed that the most optimal volume configuration was achieved at a 1:5 ratio, yielding the maximum specific absorption peak of 0.440 at a wavelength of 337.5 nm. Concurrently, pH 10 was determined to be the optimum alkaline condition, yielding a stable peak absorbance of 0.204 at 326 nm, driven by abundant hydroxyl (OH⁻) ions, which govern the rates of hydrolysis and nucleation. Structural characterization through X-Ray Diffraction (XRD) confirmed the formation of a pure hexagonal wurtzite crystal phase with high crystallinity, matching ICDD PDF No. 04-015-4060, revealing an average crystallite size of 30.5 nm. Fourier Transform Infrared (FTIR) analysis confirmed the characteristic Zn-O metal-oxygen stretching vibration at 423.22 cm⁻¹, along with organic bands (O-H, C=O, and C-O), demonstrating that the extract phytochemicals functioned effectively as natural capping agents. Lastly, Particle Size Analyzer (PSA) testing confirmed a hydrodynamic particle size of 8.44 nm with a Polydispersity Index (PDI) of 0.1729, signifying monodispersed nanoparticles with excellent uniform distribution suitable for various advanced materials and surface-dependent technological applications.

Keywords: Capping Agent; Green Synthesis; Red Betel Leaves; Sonication Method; ZnO Nanoparticles.

Introduction

Nanotechnology is a scientific field that focuses on nanoscale materials (1-100 nm), including the design and utilization of structures that have a broad impact on the electronics, health and waste processing sectors [1], [2]. Nanoparticles are crucial units because their surface area enables new material properties that are superior to those at the macro scale [3]. However, conventional synthesis methods such as sol-gel and hydrothermal methods often involve toxic organic solvents and high temperatures, thereby polluting the environment. As a sustainable solution, green synthesis offers an environmentally friendly alternative by utilizing plant extracts rich in secondary metabolites as natural capping agents [4], [5]. This phytochemical interaction not only maintains stability but also tunes the material's electronic structure (band gap engineering) by controlling light absorption [6], [7].

ZnO nanoparticles were chosen in this study due to their high stability, biocompatibility, amphoteric properties, and large specific surface area to provide catalytically active sites (O²⁻) [8]. Its potential applications are very broad, ranging from biological activities (antifungal, antibacterial, anticancer) to functional materials such as sunscreens, photocatalysts, and biodiesel catalysts.

Red betel leaf extract (*Piper crocatum*) was chosen in this study because of its abundant polyphenol, flavonoid, and tannin content [9]. These phytochemical compounds are

crucial for coating the ZnO surface, lowering the surface energy, and preventing agglomeration, thus producing a stable hexagonal wurtzite crystal structure [10]. To improve product quality, this study integrated the sonication method (Ultrasound-Assisted). Ultrasonic waves trigger acoustic cavitation, which creates local hotspots and has been shown to produce more homogeneous particles and higher crystallinity than conventional stirring [11]. This approach ensures a stable distribution of kinetic energy, thereby producing optimal sediment yield without particle mass buildup [11].

The selection of the precursor type is a key factor in the final product's crystallinity. Various zinc salts have been used as precursors in the manufacture of ZnO nanoparticles, including zinc acetate dehydrate (Zn(C₂H₃O₂)₂·2H₂O), zinc nitrate hexahydrate (Zn(NO₃)₂·6H₂O), zinc sulfate heptahydrate (ZnSO₄·7H₂O), and zinc chloride (ZnCl₂) (Shaba et al., 2021). Based on previous research, which demonstrates that the use of sulfate salts in green synthesis is effective for producing ZnO nanoparticles with high stability [12]. The use of sulfate salts for ZnO nanoparticle synthesis is still rare, so the use of zinc sulfate in this study remains focused on achieving similar characterization standards, namely the formation of a pure hexagonal wurtzite phase and optimal nanoscale particle size for catalytic activity. The novelty of this research lies in the optimization of chemical parameters through adjusting the alkaline pH (8, 10, 12) and varying the volume ratio of the extract to the

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ZnSO₄·7H₂O precursor (1:1, 1:3, 1:5). The alkaline pH conditioning plays a role in accelerating the formation of zinc hydroxide nuclei, while varying the extract ratio aims to control the crystal size. Through XRD, FTIR, UV-Vis, and PSA characterization, this study aims to produce ZnO nanoparticles with the best physicochemical characteristics. This material is projected to exhibit optimal surface reactivity and structural stability, making it highly promising as an efficient heterogeneous catalyst or functional material for various advanced environmental and chemical applications in future studies.

Research Methods

Materials

The materials used in this study were Red Betel Leaves (*Piper crocatum*) obtained from Kuningan, West Java, Zinc Sulfate heptahydrate (ZnSO₄·7H₂O), 80% Methanol, 0.1 M NaOH solution, and Aquades.

Extraction of Red Betel Leaf

Red betel leaf powder is obtained by oven-drying at 60°C for 2 days and grinding with a blender [13]. Then, 10 grams of red betel leaf powder was extracted with 100 mL of methanol by sonication for 30 minutes at 30°C [14]. The filtrate was then concentrated on a rotary evaporator at 40°C until a thick extract of red betel leaves was obtained [15].

Synthesis and Volume Optimization of Red Betel Leaf Extract

The synthesis of ZnO nanoparticles was carried out using the Ultrasound-Assisted Green Synthesis method for 30 minutes by utilizing *Piper crocatum* leaf extract as a reducing agent for the precursor of zinc sulfate heptahydrate (ZnSO₄·7H₂O). Process optimization was carried out by mixing ZnSO₄·7H₂O solution (0.1 M) and red betel extract at various volume ratios, namely 1:1, 1:3, 1:5, 1:7, and 1:9 [16].

Table 1. Composition of mixing precursor solution and extract

No.	Formulation	Volume (mL)	
		ZnSO ₄ ·7H ₂ O	Extract
1.	1:1	3.0	3.0
2.	1:3	1.5	4.5
3.	1:5	1.0	5
4.	1:7	0.75	5.25
5.	1:9	0.60	5.40

The successful formation of nanoparticles was confirmed by UV-Vis spectrophotometry. Absorbance spectra were measured over the wavelength range of 300–800 nm using a spectrophotometer to identify the characteristic absorbance peaks of ZnO [17].

Determination of Optimum pH

The pH values from the optimum volume variation results were adjusted to pH 8, 10, and 12 using a 0.1 M NaOH solution, with stirring until homogeneous for 15

minutes. After the pH was reached, the mixture was sonicated at 70°C for 30 minutes [18]. The reaction mixture was routinely monitored for visual color changes using UV-Vis spectrophotometric analysis. Absorbance spectra were measured in the wavelength range of 300–800 nm using a spectrophotometer [17].

The synthesis results that have an optimum pH are separated by centrifugation at 9,000 rpm for 30 minutes to remove the extract liquid at the top which is then discarded, and the settled nanoparticles are washed in stages, starting with the use of deionized water to remove residual inorganic reactants, and continued with washing using ethanol to minimize agglomeration and accelerate the particle dehydration process before the calcination stage [19]. The pure precipitate obtained was then dried in an oven at 70°C for 18 hours, and calcined at 450°C for 2 hours to decompose all organic compounds from the remaining leaf extract, thus obtaining pure ZnO powder and then used for particle characterization [20].

Characterisation of ZnO Nanoparticle

The results of green synthesis of ZnO nanoparticles were characterized using a X-ray Diffraction (XRD). XRD data were analyzed quantitatively using the Debye-Scherrer equation to determine the crystallite size of ZnO nanoparticles. The analysis was performed using Cu K α radiation and scanned over the 2 θ diffraction angle range of 10° to 80°. The XRD results were used to identify peaks corresponding to the ZnO structure and calculate the crystallite size of the nanoparticles [21].

$$D = \frac{0.9\lambda}{\beta \cos \theta}$$

where D is the crystallite size of zinc oxide nanoparticles (nm), 0.9 is the Scherrer constant, β is the full width at half maximum (FWHM) of the diffraction peak expressed in radians, λ is the X-ray wavelength (typically 0.15406 nm for CuK α radiation), and θ is the Bragg diffraction angle (half of the experimental 2 θ position).

The second is characterized by particle size analysis (PSA). This analysis was used to analyze the particle size distribution range of the synthesized ZnO nanoparticles. The particle size distribution approach was employed for this study. To accomplish this, the liquid sample containing ZnO NPs was diluted by a factor of ten using Milli-Q. Subsequently, the solution was subjected to centrifugation, and the resultant solution was analyzed in a cuvette [22].

The third was characterized by FTIR spectroscopy. The samples were tested over the absorption range, with wavelengths from 4000 cm⁻¹ to 400 cm⁻¹ [21].

Results and Discussion

In this study, ZnO nanoparticles were synthesized using a biosynthetic method. This biosynthetic method utilizes organic compounds found in plants. Organic compounds found in plants have potential as bioreductants because they can function as reducing agents and stabilizing agents for ZnO nanoparticles. The plant used in this study was the red betel leaf.

Red Betel Leaf Preparation (*Piper crocatum*)

Organic compounds found in plants have potential as bioreductants because they can function as reducing agents and stabilizers for ZnO nanoparticles. The plant used in this study was red betel leaf. Red betel leaves obtained online were cleaned with running water, dried in an oven at 60°C for 7 days (42 hours), and ground with a blender. A 30-minute sonication soak in methanol effectively extracted polar secondary metabolites, including phenolics and flavonoids, from red betel leaf powder. The use of fine powder increased the contact surface area between the reactants, maximizing extraction efficiency. After filtration and evaporation, a viscous extract rich in bioactive molecules was obtained, which serves as a natural capping agent.

Synthesis and Extract Volume Optimization

Green synthesis of ZnO nanoparticles used a bottom-up approach by reacting 0.1 M $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ precursor with varying volumes of red betel leaf extract through sonication for 30 minutes (30°C). Ultrasonic waves trigger acoustic cavitation, which generates significant energy to support redox reactions and prevent agglomeration. Confirmation of formation and determination of the optimum ratio were analyzed using a UV-Vis spectrophotometer in the 200–800 nm range.

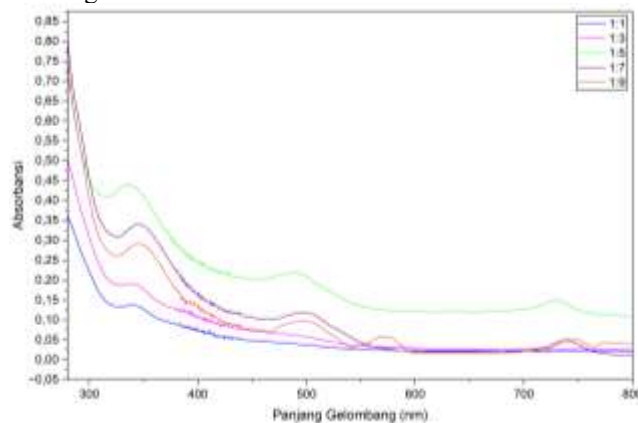


Figure 1. Results of ZnO nanoparticles at varying volume ratios

The results of the UV-Vis spectrophotometer are as shown in Figure 2. The absorption peak in the range of 336–346 nm is the specific excitation region of ZnO nanoparticles. This range is the ultraviolet region for ZnO nanoparticles. ZnO nanoparticles are absorbers of the ultraviolet light region [23]. The results of the maximum wavelength characterization using the UV-Vis spectrum in the comparison of variations in red betel leaf extract (*Piper crocatum*) with precursors are presented in Figure 3.

The difference in absorbance values in each comparison is influenced by the volume of precursor and red betel leaf extract. Based on Table 2, the optimum volume ratio of precursor to red betel leaf extract is 1:5, with a precursor volume of 1 mL and a red betel leaf extract volume of 5 mL. The optimum volume ratio can be seen in the largest absorbance on the UV-Vis spectrophotometer at a 1:5 ratio, 0.440. This optimum value indicates that the extract's ability to reduce and the number of ZnO nanoparticles formed are

greater. Here, red betel leaf extract serves as a capping agent that maintains the stability of ZnO nanoparticles.

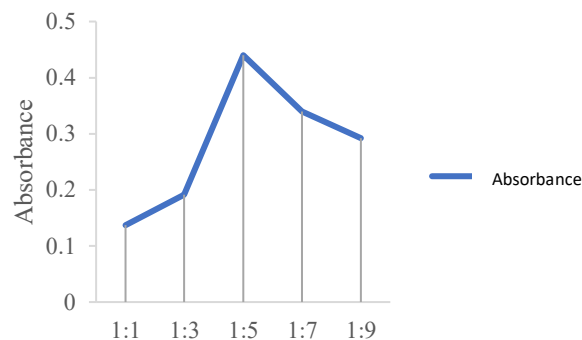


Figure 2. Results of the UV-Vis spectrophotometer measurements of ZnO nanoparticles with variations in the ratio of precursors and extracts

Determination of Optimum pH

pH optimization was carried out at the best ratio (1:5) with pH variations of 8, 10, and 12 using 0.1 M NaOH. Measurements were carried out over the wavelength range 200–800 nm with a methanol blank, and the results are shown in Figure 3.

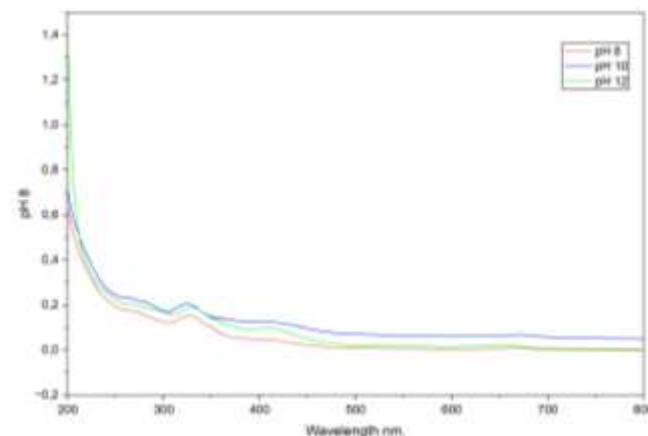


Figure 3. Characterization results of pH variations using a UV-Vis spectrophotometer

pH 10 was found to be the optimum pH condition, as seen from the highest absorbance peak at pH 10 with an absorbance of 0.204 (Table 3.). This means that pH 10 is the most stable condition and yields more nanoparticles.

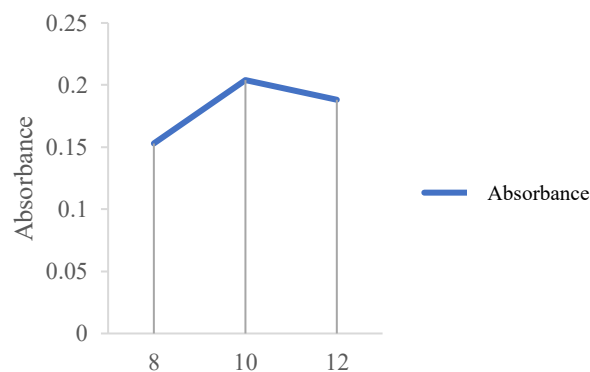


Figure 4. UV-Vis spectrophotometer measurement results of ZnO nanoparticles using pH variations

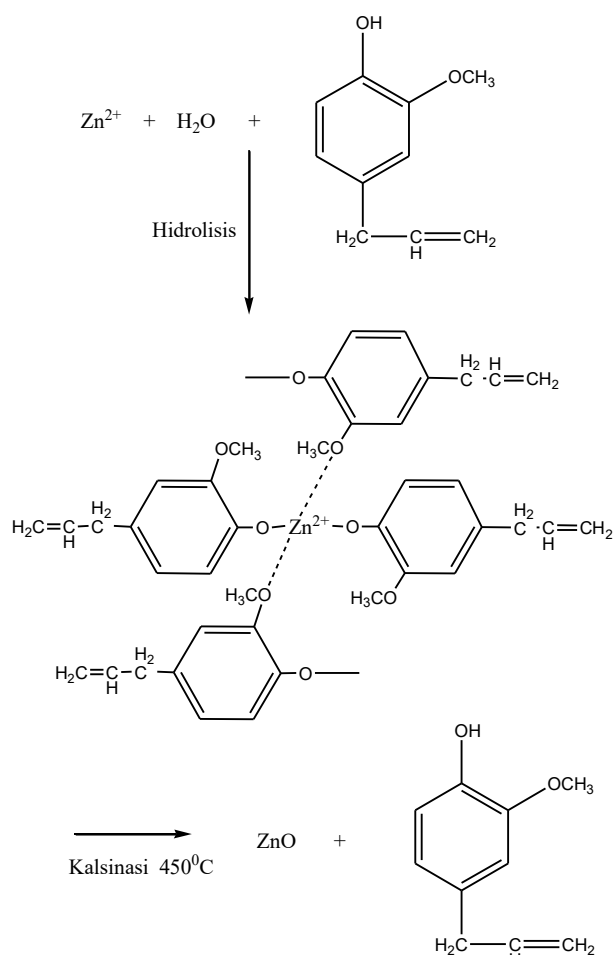
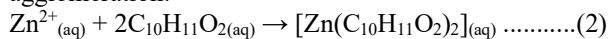
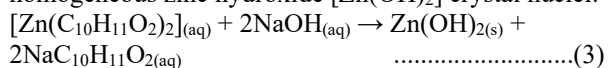


Figure 5. The reaction mechanism of ZnO particle formation with eugenol capping agent

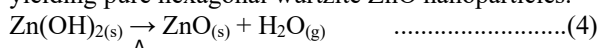
pH 10 was determined as the best condition. The ultrasound-assisted green synthesis of ZnO nanoparticles using red betel leaf extract involves several sequential chemical reactions. Initially, the zinc sulfate heptahydrate precursor completely dissociates in the aqueous medium to release free zinc ions (Zn^{2+}) as described in Equation (1): $ZnSO_4 \cdot 7H_2O_{(s)} \rightarrow Zn^{2+}_{(aq)} + SO_4^{2-}_{(aq)} + 7H_2O_{(l)}$ (1) Subsequently, the active phytochemical compounds present in the red betel leaf extract, particularly eugenol, act as natural capping agents. The hydroxyl (-OH) groups of the eugenol compound undergo complexation with the free Zn^{2+} ions to form a stable zinc-eugenolate complex, which effectively restricts premature particle growth and prevents severe agglomeration:



Upon the addition of 0.1 M NaOH solution to reach the optimum alkaline condition of pH 10, the abundance of hydroxyl ions (OH^-) induces the hydrolysis and electrostatic condensation of the complex. This step prompts the deprotonation and precipitates the zinc ions into stable and homogeneous zinc hydroxide [$Zn(OH)_2$] crystal nuclei:



Finally, during thermal calcination at $450^\circ C$, the collected [$Zn(OH)_2$] precipitate undergoes thermal decomposition via dehydration. This stage successfully removes the volatile organic structural elements from the remaining leaf extract, yielding pure hexagonal wurtzite ZnO nanoparticles:



The visual schematic of this proposed mechanism for the formation of ZnO nanoparticles with eugenol as a capping agent is illustrated in Figure 6. [24], [25]

X-ray Diffraction (XRD) Characterization

The physical characterization results of ZnO nanoparticles were tested using an X-ray Diffraction (XRD) instrument to determine the crystallite size. The resulting spectra of the ZnO sample are shown in Figure 4.6.

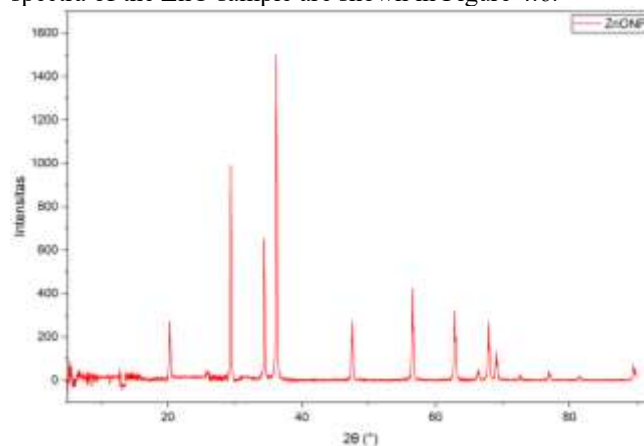


Figure 6. XRD diffraction of ZnO nanoparticles from red betel leaf extract

The X-ray diffraction pattern shows characteristic peaks at angles 2θ 36.2° ; 34.4° ; 29.3° ; 47.5° ; 56.5° ; 62.8° ; 67.9° ; 69.1° which correspond to the Miller indices of the crystal planes (100), (002), (101), (102), (110), (103), (112), and (201). These characteristics confirm the formation of a pure ZnO crystal phase with a hexagonal wurtzite structure, in accordance with the ICDD PDF No. 04-015-4060 standard, without any other impurity peaks. The sharp peaks indicate a high degree of crystallinity. Based on all the diffraction peaks, the average crystallite size is 30.5 nm.

This reduction in crystallite size significantly affects the material's physicochemical properties by substantially increasing the specific surface area and creating a higher density of active crystal phases at the nanoparticle surface. The formation of a pure, highly crystalline ZnO phase at the nanometer scale provides superior surface reactivity and better accessibility for interacting molecules. This ensures minimized mass transfer resistance and optimal surface-to-volume efficiency, which makes the synthesized nanoparticles highly advantageous for various surface-dependent and advanced technological applications.

Particle Size Analysis (PSA) Characterization

Based on the PSA results of ZnO nanoparticles from red betel leaf extract, the average ZnO particle size was 8.44 nm using Dynamic Light Scattering (DLS) or laser diffraction. The particle size obtained was in the 1-100 nm interval, so the synthesized ZnO nanoparticles met the nanoparticle size [26]. This particle size of 8.44 nm has a very significant effect on its surface reactivity and physical stability. In line with the fundamental principles of nanomaterial characterization, a smaller particle size directly translates to an exponentially higher specific surface area, thereby maximizing the exposure of surface active sites. Furthermore, achieving an ultra-small size within the

nanopmeter scale without severe aggregation indicates that the system possesses high electrostatic or steric stabilization, which prevents particle sedimentation and enhances its efficiency in various surface-dependent reactions.

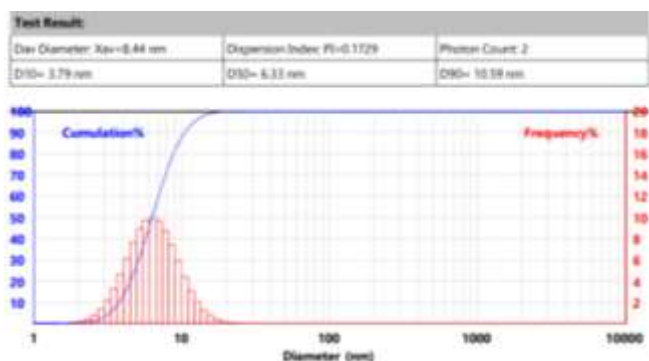


Figure 7. Characterization results of ZnO nanoparticles using PSA

The difference between XRD crystallite size and PSA hydrodynamic particle size measurements is that XRD measures crystallite size (the size of coherent single-crystal domains) in the dry powder state using the Debye-Scherrer equation. Meanwhile, PSA measures the hydrodynamic diameter of particles or aggregates suspended in a liquid medium. In this study, the smaller size obtained from PSA (8.44 nm) compared to XRD (30.5 nm) indicates that the ultrasonic-assisted sonication method used during synthesis was highly effective in dispersing nanoparticles and preventing the formation of larger aggregates in the liquid suspension. Furthermore, phytochemicals from red betel leaf extract acted as highly efficient capping agents, stabilizing fragmented ultra-small nanoparticles in solution, further supported by the low Polydispersity Index (PDI).

The PSA measurement results showed a polydispersity index of 0.1729. The polydispersity index is a numerical parameter that quantifies the degree of non-uniformity (heterogeneity) in particle size within a sample. Another term is the heterogeneity index. A polydispersity index value close to zero indicates that the resulting nanoparticles are stable and well-distributed [27]. Monodisperse conditions ensure that the particles do not readily agglomerate (clump) due to kinetic and thermal effects during the reaction's stirring and heating [28].

FTIR Spectroscopy Characterization

The chemical characterization of ZnO nanoparticles was carried out using a Fourier Transform Infra-Red (FTIR) instrument to identify functional groups in the samples. The functional group identification results for the ZnO nanoparticle sample from red betel leaf extract are shown in Figure 6.

The 3400-3500 cm^{-1} band, which represents the O-H absorption region, is formed due to the adsorption of H_2O during the nanoparticle synthesis process. The presence of this O-H group indicates the involvement of biomolecules in the reduction of Zn^{2+} ions and acts as a stabilizing agent during nanoparticle growth [29], [30]. This absorption region also originates from adsorbed water molecules and phenolic compounds contained in the red betel leaf extract [31], [30]. The 1650-1750 cm^{-1} band, the C=O absorption region, indicates that some biomolecules are adsorbed on or still

bound to the surface of ZnO nanoparticles after synthesis [32], [33]. Meanwhile, the 1000-1150 cm^{-1} band is the C-O absorption region, which generally originates from polysaccharides in leaf extracts [34], [35]. The presence of these organic bands indicates that red betel leaf extract serves as a natural capping agent, helping control the growth and stability of nanoparticles [30]. The distinctive absorption band that appears at wavenumbers below 600 cm^{-1} is associated with the Zn-O absorption region, which is the main characteristic of ZnO phase formation [36]. The presence of Zn-O absorption bands and surface organic bands indicates that ZnO nanoparticles were successfully formed through the green synthesis process, using plant biomolecules that act as nucleation and particle-growth controllers without disrupting the formation of the ZnO crystal structure.

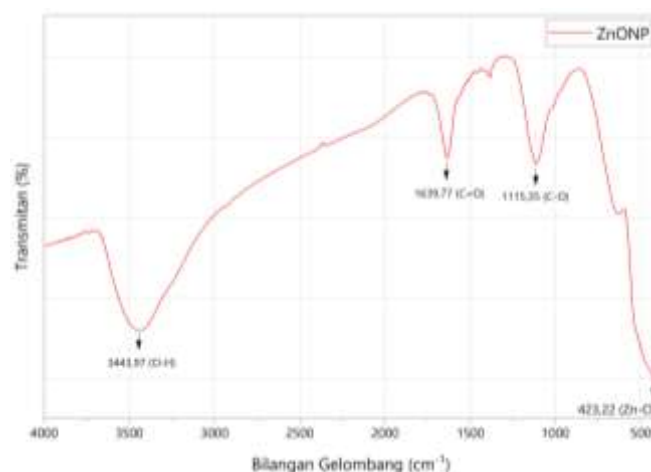


Figure 8. FTIR spectra of ZnO nanoparticles

The functional group identification results for the ZnO nanoparticles using FTIR are presented in Table 4.5.

Table 2. Results of functional group identification

Wavenumber (cm^{-1})	Functional Group
ZnO nanoparticles	
3443.97	O-H
1639.77	C=O
1115.35	C-O
423.22	Zn-O

Conclusion

The green synthesis of pure ZnO nanoparticles with hexagonal wurtzite structure using sonication was successfully optimized at a precursor volume ratio to red betel leaf extract (*Piper crocatum*) of 1:5 and alkaline conditions of pH 10. This process produced superior physicochemical characteristics in the form of a crystallite size of 30.5 nm, confirmation of Zn-O bonds and organic capping agent coating through FTIR analysis, and a very small average hydrodynamic particle size of 8.44 nm with stable monodispersity properties (PDI 0.1729), so this material yielding highly stable nanoparticles with favorable monodispersity properties (PDI 0.1729). Consequently, these outstanding physicochemical characteristics confirm that the ultrasound-assisted green synthesis successfully produces high-quality ZnO nanoparticles with excellent prospects for various surface-dependent and advanced material applications. Further studies involving statistical

replicates and optimization error bars are recommended to enhance the statistical significance of the synthesis parameters. Additionally, future research should evaluation, or biological applications to fully explore the functional capabilities of the synthesized ZnO nanoparticles.

Author's Contribution

L. Isyrak: Conceptualization, data collection, data analysis, manuscript drafting. A. P. Purnamasari: Methodology, data collection, critical manuscript review, manuscript revision. All authors contributed to the writing of this article.

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References

- [1] D. Zhang, X. Ma, Y. Gu, H. Huang, and G. Zhang, "Retracted: Green Synthesis of Metallic Nanoparticles and Their Potential Applications to Treat Cancer," *Front. Chem.*, vol. 8, Oct. 2020, doi: 10.3389/fchem.2020.00799.
- [2] S. Malik, K. Muhammad, and Y. Waheed, "Nanotechnology: A Revolution in Modern Industry," Jan. 01, 2023, *MDPI*. doi: 10.3390/molecules28020661.
- [3] K. N. Thakkar, S. S. Mhatre, and R. Y. Parikh, "Biological synthesis of metallic nanoparticles," *Nanomedicine*, vol. 6, no. 2, pp. 257–262, Apr. 2010, doi: 10.1016/j.nano.2009.07.002.
- [4] Y. Y. Chan, Y. L. Pang, S. Lim, and W. C. Chong, "Facile green synthesis of ZnO nanoparticles using natural-based materials: Properties, mechanism, surface modification and application," *J. Environ. Chem. Eng.*, vol. 9, no. 4, p. 105417, Aug. 2021, doi: 10.1016/j.jece.2021.105417.
- [5] T. Amrillah, C. A. C. Abdullah, A. Hermawan, F. N. I. Sari, and V. N. Alvani, "Towards Greener and More Sustainable Synthesis of MXenes: A Review," Dec. 01, 2022, *MDPI*. doi: 10.3390/nano12234280.
- [6] Z. Villagrán *et al.*, "Plant-Based Extracts as Reducing, Capping, and Stabilizing Agents for the Green Synthesis of Inorganic Nanoparticles," Jun. 01, 2024, *Multidisciplinary Digital Publishing Institute (MDPI)*. doi: 10.3390/resources13060070.
- [7] M. Abisha Meji, D. Usha, B. M. Ashwin, A. Yardily, and M. S. Dennison, "Microwave-assisted green synthesized ZnO nanoparticles: an experimental and computational investigation," *Discover Applied Sciences*, vol. 7, no. 3, Mar. 2025, doi: 10.1007/s42452-025-06563-8.
- [8] A. Wang, W. Quan, H. Zhang, H. Li, and S. Yang, "Heterogeneous ZnO-containing catalysts for efficient biodiesel production," Jun. 08, 2021, *Royal Society of Chemistry*. doi: 10.1039/d1ra03158a.
- [9] R. A. K. Sihombing, D. S. Napitupulu, S. R. Bangun, and S. R. Sitindaon, "Uji Daya Hambat Daun Sirih Merah (piper crocatum) terhadap Bakteri mycobacterium tuberculosis," *Jurnal Kesehatan Tambusai*, vol. 5, Dec. 2024.
- [10] M. Naseer, U. Aslam, B. Khalid, and B. Chen, "Green route to synthesize Zinc Oxide Nanoparticles using leaf extracts of Cassia fistula and Melia azadarach and their antibacterial potential," *Sci. Rep.*, vol. 10, no. 1, Dec. 2020, doi: 10.1038/s41598-020-65949-3.
- [11] K. Bhandari *et al.*, "A comparative investigation of ultrasonication and magnetic stirring methods for green synthesis of zinc oxide nanoparticles using Punica granatum peels," *Sci. Rep.*, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-04926-0.
- [12] Asma, F. Ali, T. Salam, and S. Syed, "Green synthesis of Zinc oxide nanoparticles from fresh curcuma longa tuber and their anti-bactericidal and photocatalytic activity," *Bioscience Research*, 2021, [Online]. Available: www.isisn.org
- [13] S. Singh, H. Gupta, P. Sharma, and S. Sahi, "Advances in Artificial Intelligence (AI)-assisted approaches in drug screening," *Artificial Intelligence Chemistry*, vol. 2, no. 1, p. 100039, Jun. 2024, doi: 10.1016/j.aichem.2023.100039.
- [14] A. Ardiansyah and A. T. Wicaksono, "Variasi Konsentrasi Senyawa Fitokimia Sirih Merah Dan Pelarut Heksana Menggunakan Gas Chromatography – Mass Spectrometry," *Al Kawnu : Science and Local Wisdom Journal*, vol. 3, no. 2, pp. 36–43, Jul. 2024, doi: 10.18592/ak.v3i2.11752.
- [15] S. E. Cahyaningrum, A. P. Wardana, F. I. Muhaimin, A. P. Purnamasari, B. Nugroho, and M. B. Misran, "Potential of Nanoencapsulated Curcuma longa- Andrographis paniculata as an Anticancer Agent," *Tropical Journal of Natural Product Research*, Feb. 2025, doi: <https://doi.org/10.26538/tjnpr/v9i2.6>.
- [16] J. Sarkar, M. Ghosh, A. Mukherjee, D. Chattopadhyay, and K. Acharya, "Biosynthesis and safety evaluation of ZnO nanoparticles," *Bioprocess Biosyst. Eng.*, vol. 37, no. 2, pp. 165–171, Feb. 2014, doi: 10.1007/s00449-013-0982-7.
- [17] S. Ahmed *et al.*, "Green synthesis of zinc nanoparticles and their effects on growth and yield of Pisum sativum," *J. King Saud Univ. Sci.*, vol. 34, no. 6, p. 102132, Aug. 2022, doi: 10.1016/j.jksus.2022.102132.
- [18] M. Aliannezhadi, F. Doost Mohamadi, M. Jamali, and F. Shariatmadar Tehrani, "Ultrasound-assisted green synthesized ZnO nanoparticles with different solution pH for water treatment," *Sci. Rep.*, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-90305-8.
- [19] S. T. Karam and A. F. Abdulrahman, "Green Synthesis and Characterization of ZnO Nanoparticles by Using Thyme Plant Leaf Extract," *Photonics*, vol. 9, no. 8, Aug. 2022, doi: 10.3390/photonics9080594.
- [20] S. S. Alias, A. B. Ismail, and A. A. Mohamad, "Effect of pH on ZnO nanoparticle properties synthesized by sol-gel centrifugation," *J. Alloys Compd.*, vol. 499, no. 2, pp. 231–237, Jun. 2010, doi: 10.1016/j.jallcom.2010.03.174.
- [21] F. A. Barrios-Navarro, A. R. Vilchis-Nestor, and P. A. Luque, "Green-synthesized ZnO nanoparticles via Mamea americana extract: Characterization and multidye photocatalytic degradation," *Inorg. Chem. Commun.*, vol. 182, Dec. 2025, doi: 10.1016/j.inoche.2025.115672.

- [22] R. K. Rusli *et al.*, "Green synthesis of zinc oxide nanoparticles utilizing extract from *Garcinia mangostana* leaves: Characterization and optimization of calcination temperature," *J. Adv. Vet. Anim. Res.*, vol. 11, no. 3, pp. 573–582, Sep. 2024, doi: 10.5455/javar.2024.k807.
- [23] A. N. Rozi and H. Saragih, "Sintesis Nanopartikel ZnO Menggunakan Prekursor ZnCl₂ dan Polimer Penstabil Tween 80 untuk Aplikasi Tabir Surya," *Jurnal Fisika Unand*, vol. 14, no. 6, pp. 585–594, Nov. 2025, doi: 10.25077/jfu.14.6.585-594.2025.
- [24] N. M. Musfita, F. Fajaroh, A. Aliyatulmuna, E. Ciptawati, Y. Yahmin, and N. Nazriati, "Pemanfaatan Limbah Kulit Pisang Raja Nangka sebagai Capping Agent Sintesis Partikel ZnO: Variasi Pelarut Ekstraksi," *Sainmatika: Jurnal Ilmiah Matematika dan Ilmu Pengetahuan Alam*, pp. 124–140, Dec. 2022, doi: 10.31851/sainmatika.v19i2.9135.
- [25] Y. Yunita, N. Nurlina, and I. Syahbanu, "Sintesis Nanopartikel Zink Oksida (ZnO) dengan Penambahan Ekstrak Klorofil sebagai Capping Agent," *POSITRON*, vol. 10, no. 2, p. 44, Dec. 2020, doi: 10.26418/positron.v10i2.42136.
- [26] J. M. Teulon *et al.*, "On the operational aspects of measuring nanoparticle sizes," *Nanomaterials*, vol. 9, no. 1, Jan. 2019, doi: 10.3390/nano9010018.
- [27] M. Danaei *et al.*, "Impact of particle size and polydispersity index on the clinical applications of lipidic nanocarrier systems," May 18, 2018, *MDPI AG*. doi: 10.3390/pharmaceutics10020057.
- [28] O. Oehlsen, S. I. Cervantes-Ramírez, P. Cervantes-Avilés, and I. A. Medina-Velo, "Approaches on Ferrofluid Synthesis and Applications: Current Status and Future Perspectives," *ACS Omega*, vol. 7, no. 4, pp. 3134–3150, Feb. 2022, doi: 10.1021/acsomega.1c05631.
- [29] A. R. M. Amin *et al.*, "Deteksi simultan kontaminasi DNA babi dan alkohol pada produk makanan Jepang menggunakan Spektroskopi FTIR, GC-MS dan real time-PCR," *Teknosains: Media Informasi Sains dan Teknologi*, Jan. 2026, doi: <https://doi.org/10.24252/teknosains.v20i1.64648>.
- [30] D. Hizhar, S. Handani, and Elvaswer, "Sintesis Hijau dan Karakterisasi Nanopartikel ZnO Menggunakan Ekstrak Daun Kelapa Sawit (*Elaeis guineensis*)," *Jurnal Fisika Unand*, vol. 15, no. 2, pp. 236–243, Apr. 2026, doi: 10.25077/jfu.15.2.236-243.2026.
- [31] H. W. Amini *et al.*, "Optimasi Ekstraksi Senyawa Fenolik Daun Sirih Merah (*Piper Crocatum* Ruitz & Pav) Menggunakan Metode Microwave Assisted Extraction (MAE)," *Dalton: Jurnal Pendidikan Kimia dan Ilmu Kimia*, vol. 7, no. 3, p. 222, Dec. 2024, doi: 10.31602/dl.v7i3.16431.
- [32] M. F. Islam *et al.*, "Green synthesis of zinc oxide nano particles using *Allium cepa* L. waste peel extracts and its antioxidant and antibacterial activities," *Heliyon*, vol. 10, no. 3, Feb. 2024, doi: 10.1016/j.heliyon.2024.e25430.
- [33] J. Miedzianowska-Masłowska, M. Masłowski, and K. Strzelec, "Alfalfa/Lucerne (*Medicago sativa*) as a Source of Functional Bioadditives for Elastomeric Natural Rubber Composites," *Polymers (Basel)*, vol. 16, no. 23, Dec. 2024, doi: 10.3390/polym16233444.
- [34] S. Agatonovic-Kustrin, P. Ristivojevic, V. Gegechkori, T. M. Litvinova, and D. W. Morton, "Essential oil quality and purity evaluation via ft-ir spectroscopy and pattern recognition techniques," *Applied Sciences (Switzerland)*, vol. 10, no. 20, pp. 1–12, Oct. 2020, doi: 10.3390/app10207294.
- [35] I. N. E. Lister, *Daun Sirih Merah Manfaat Untuk Kesehatan*. Medan: Unpri Press, 2020.
- [36] A. Barkhordari, H. R. Mashayekhi, P. Amiri, S. Özçelik, F. Hanife, and Y. Azizian-Kalandaragh, "Performance of machine learning algorithms in spectroscopic ellipsometry data analysis of ZnTiO₃ nanocomposite," *Sci. Rep.*, vol. 14, no. 1, Dec. 2024, doi: 10.1038/s41598-023-50620-4.