



Calcination temperature-dependent structural and photocatalytic properties of green-synthesized ZnO nanostructures using *Mitragyna speciosa* leaf extract

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Abstract

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ZnO nanostructures were prepared by a green synthesis route using *Mitragyna speciosa* Korth. leaf extract as a natural reducing agent in deionized (DI) water. The effect of calcination temperatures on the material properties of green-synthesized ZnO was systematically investigated. Calcination temperatures ranging from 250 to 550 °C were selected to facilitate the complete decomposition of precursor compounds and residual organic components, considering the thermal stability of ZnO and plant-derived organic species. ZnO nanostructures were characterized by XRD to identify crystallinity, FE-SEM to observe surface morphology, FTIR to confirm chemical bonding, and BET analysis to measure specific surface area. The obtained ZnO photocatalyst was evaluated through rhodamine B (RhB) dye degradation assisted by the piezo-catalytic effect. The crystallinity, morphology, chemical bonding, surface area, and photocatalytic activity of naturally derived ZnO nanostructures were significantly altered by the calcination temperature, demonstrating their promise for environmental remediation

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1. Introduction

In recent years, nanomaterials have attracted considerable attention due to their superior properties, including tunable size-dependent characteristics, high surface-to-volume ratio, improved electrical conductivity, mechanical reinforcement capability, and adaptable surface reactivity [1]. These prominent features with multifunctional integration make nanomaterials promising candidates for a diverse range of applications, such as catalysis, sensors, agriculture, electronics, and advanced engineering systems [2]. Among the various classes of nanomaterials, metal oxides (MOs) have been universally investigated owing to their tunable electronic band structures, rich defect chemistry, morphological versatility, chemical and thermal stability, low-cost of fabrication, and diverse functional properties [3]. Previous studies have reported that MOs such as tungsten oxide (WO₃), zinc oxide (ZnO), titanium dioxide (TiO₂), and iron oxide (Fe₂O₃) are widely applied in photocatalysis, gas sensing, antimicrobial activity, and environmental remediation [4 – 6]. These materials are particularly attractive because of their abundant oxygen vacancies, suitable semiconductor band gaps, high photoactivity, and strong surface reactivity.

In particular, their semiconducting nature enables effective light absorption and charge carrier generation, which are essential for photocatalytic applications.

Zinc oxide (ZnO) represents a multifunctional MO material that has been widely used in cosmetics, rubber, ceramics, electronics, and antibacterial fields. In particular, it has gained a lot of attention in the field of photocatalysis [7]. Its wide band gap, high thermal stability, and strong capability for the degradation of dyes and pollutants under ultraviolet (UV) activation which generates reactive oxygen species (ROS) make ZnO an outstanding photocatalyst for wastewater treatment [8]. Numerous synthesis methods have been developed for ZnO production, and this has led to the development of various forms of ZnO that possess a wide range of physicochemical properties. Conventional synthesis approaches can be broadly classified into chemical and physical methods. Chemical methods include co-precipitation, sol-gel methods, chemical vapor process, hydrothermal synthesis, while physical methods commonly involve ball milling processes, laser pyrolysis, pulse vapor deposition, and lithographic techniques [9 – 11]. Although these techniques can yield ZnO products with high purity and fine particle size, they often require high

temperatures, substantial energy consumption, complicated processing steps, and the use of hazardous chemical precursors, which leads to less sustainability for long-term applications [12]. To overcome these limitations, green synthesis methods employing biological resources as reducing and stabilizing agents have emerged as environmentally friendly alternatives.

Green synthesis approaches replace conventional chemical reagents with natural extracts derived from plants, bacteria, algae, yeasts, or fungi as summarized in Table 1 [13]. During nanoparticle formation, the biological extracts contain phytochemicals including protein, flavonoids, alkaloids, polyphenols, and tannins, which function as reducing agents, capping agents, and stabilizing agents [14]. As a result, green synthesis enhances environmental compatibility while offering long-term sustainability, cost-effectiveness, and reduced toxicity [15]. Additionally, the utilization of locally available natural resources not only enhances the safety and sustainability of nanomaterials but also increases value to local plants and supports local economic development [16]. The successful green method of ZnO nanostructures using different plant organs, including leaves, peels, flowers, seeds, and roots has been reported in several studies. Various plant extracts—such as orange peel, loquat seed, banana flower,

Garcinia mangostana leaf, and *Scutellaria baicalensis* root—have been reported as effective natural resources for the eco-friendly method of ZnO nanoparticles [17–21].

Mitragyna speciosa Korth., commonly known in Thailand as Kratom, is a plant native to Africa and Asia, with widespread distribution in Southeast Asia [22]. The leaves of *Mitragyna speciosa* have long been used in traditional Thai medicine for the treatment of ailments such as pain, abdominal discomfort, and diarrhea. Phytochemical analyses have shown that *Mitragyna speciosa* leaves contain numerous phytochemicals, including polyphenols, stilbenes, alkaloids, flavonoids, and terpenoids [23]. The roles of these phytochemicals in the leaf extract have been reported in previous studies, which show that the leaf extract contains various secondary metabolites providing functional groups, such as hydroxyl (–OH) and carbonyl (C=O) groups. These functional groups can coordinate with Zn^{2+} ions to form intermediate complexes, which subsequently promote nucleation and regulate the growth of ZnO nanostructures. These phytochemicals can act as natural reducing, capping, and stabilizing agents, facilitating the nucleation and growth of ZnO nanostructures in the green synthesis process [24].

Table 1 Comparison of natural extracts derived from different sources for green synthesis.

Natural extracts	Advantages	Disadvantages
Plants	Simple, cost-effective, efficient, scalable, and eco-friendly	Variation in extract composition depending on plant sources
Bacteria	Biocompatible, eco-friendly, easy to reproduce, non-toxic	Requires sterile culture conditions and a longer time
Fungi	Easy to scale up and downstream processing, low cost, and eco-friendly	Requires controlled growth conditions and low reproducibility
Algae	Biocompatible, low cost, eco-friendly, lack of toxic by-products	Limited size control and limited scale-up synthesis

In the green synthesis process, critical parameters—including extract concentration, metal precursor type, pH, reaction temperature, and calcination conditions—strongly influence the particle size, crystallinity, and surface chemistry of nanomaterial products. Among these parameters, calcination temperature plays a key role in determining the formation and evolution of ZnO nanostructures [25]. In this study, ZnO nanostructures were synthesized using *Mitragyna speciosa* leaf extract, and the effects of different calcination temperatures on their structural, morphological, and photocatalytic properties were systematically investigated. Additionally, the piezo-assisted photocatalytic performance of green-synthesized ZnO catalysts was evaluated using Rhodamine B (RhB) as a model compound for degradation, owing to its relatively complex aromatic structure and higher molecular mass compared with other commonly used dyes [26].

2. Materials and Methods

Materials

Mitragyna speciosa Korth. leaves (Kratom leaves) were used as a natural staple of bioactive compounds. The zinc salt precursor chosen was zinc acetate dihydrate [$\text{Zn}(\text{CH}_3\text{CO}_2)_2 \cdot 2\text{H}_2\text{O}$] from Sigma-Aldrich.

Preparation of aqueous extract and green-synthesized ZnO nanostructures

Fresh *Mitragyna speciosa* leaves were cleaned several times with DI water to eliminate contaminants, dried for 12 h at 70 °C in an oven, and crushed into a fine powder. Subsequently, 2 g of the leaf powder was dispersed in 10 mL of DI water to prepare the plant extract. The mixture was shaken at 250 rpm for 1 h and incubated in a water bath at 60 °C for 1 h to enhance the release of phytochemicals. The mixture was filtered to obtain the *Mitragyna speciosa* leaf

extract. Thereafter, 2 g of zinc acetate was dissolved in 10 mL of the leaf extract following by stirring for 1 h. The suspension was incubated in a water bath for 1 h at 60 °C and then dried at 100 °C for 12 h. Finally, the specimen was calcined ranging from 250°C to 550°C for 2 h to obtain naturally derived ZnO nanostructures.

Material Characterizations

The morphological, structural, chemical, and optical properties of the synthesized ZnO nanostructures were characterized using a comprehensive of techniques. Field-emission scanning electron microscope (FE-SEM, JEOL JSM-7610F) was employed to investigate the surface morphology. X-ray diffractometer (XRD, Rigaku SmartLab) was used to examine the crystallinity of the ZnO nanostructures. Fourier-transform infrared spectroscopy (FTIR, PerkinElmer Spectrum Two) was used to analyze the chemical bonds and functional groups in the ZnO nanostructures. Brunauer–Emmett–Teller (BET) surface area analysis was conducted to determine the specific surface area of the ZnO nanostructures.

The evaluation of photocatalytic performance

The photocatalytic performance of the green-synthesized ZnO nanostructures was determined by monitoring the degradation of Rhodamine B (RhB) under UV irradiation. Briefly, 0.02 g of the ZnO catalyst was dispersed in 10 mL of a 10 µM RhB solution and stirred in the dark for 30 min to establish adsorption–desorption equilibrium. The suspension was then irradiated with a 300-W xenon lamp for 1 h, with samples collected every 15 min to monitor the time-dependent degradation. For the piezo-assisted photocatalytic experiment, an ultrasonic bath (70 W, 40 kHz) was used to provide mechanical stimulation during light irradiation, with the sample positioned at the center of the bath. After the degradation process, the residual RhB concentration was determined by measuring the absorbance using a UV–Vis spectrophotometer (Thermo Scientific Helios Gamma). The degradation efficiency was calculated from the normalized absorbance of RhB (A/A_0) as a function of irradiation time, where A_0 is the initial absorbance of the dye solution, and A is the absorbance at the irradiation time. According to the Beer–Lambert law, the absorbance (A) is directly proportional to the concentration (C) of the compound in solution [27]. Therefore, absorbance can be used as a substitute for concentration, and the ratio A/A_0 represents the relative concentration (C/C_0) of RhB during the degradation process.

3. Results and Discussion

The morphological evolution of the green-synthesized ZnO nanostructures as a function of calcination temperature

was examined from FE-SEM images, which are shown in Fig.1. The as-prepared samples (before calcination) and the samples calcined at 250 °C mainly exhibit a mixture of triangular-like and rod-like morphologies as presented in magnified of FE-SEM images, with average particle sizes of approximately 381 and 346 nm, respectively. These morphological features are likely associated with the presence of residual bioactive compounds originating from the *Mitragyna speciosa* leaf extract, as well as untreated zinc precursor species on the particle surfaces. These organic compounds may function as capping or stabilizing agents, influencing crystal growth along specific directions [28 – 30]. This anisotropic growth resulted in the formation of the triangular-like and rod-like ZnO nanostructures that preferentially develop at relatively low calcination temperatures. Upon calcination at 350 °C, the particles exhibit dense agglomeration with a reduced average size of approximately 184 nm. The decrease in particle size can be ascribed to evaluate thermal energy, which facilitates the decomposition of residual organic species and enhances the ZnO crystallinity. Meanwhile, the morphology of the product at 450 °C transforms significantly from triangular and rod-like to predominantly spherical particles (~117 nm in average diameter). Therefore, the morphological evolution is attributed to sufficient calcination temperature, which removes residual organic compounds, reduces directional growth constraints and promotes more isotropic particle growth. At 550 °C, ZnO nanostructures retain their spherical morphology, with the average diameter increasing to approximately 156 nm. The enlargement can be ascribed to thermal sintering effect leading to particle coalescence and grain growth driven by surface energy minimization [31].

The elemental composition of the green-synthesized ZnO nanostructures was examined by energy-dispersive X-ray spectroscopy (EDS), and the calculated Zn/O atomic ratios are summarized in Table 2. The as-prepared and 250 °C samples exhibit relatively low Zn/O ratios of 0.65–0.68, which can be attributed to incomplete decomposition of residual organic species from the *Mitragyna speciosa* leaf extract and the presence of oxygen-rich surface groups. When the calcination temperature increases to 350 °C, the Zn/O ratio increases significantly to 1.49, suggesting the formation of a Zn-rich or oxygen-deficient structure influenced by thermal decomposition of precursor compounds and the removal of hydroxyl or oxygen-containing surface species. At higher calcination temperatures of 450 °C and 550 °C, the Zn/O ratios approach the stoichiometric composition of ZnO, ranging from 0.75 to 1.06, which is nearly the theoretical ZnO stoichiometric ratio of approximately 1:1. These results indicate that calcination temperature plays an important role in controlling the compositional stoichiometry and defect structure of the ZnO nanostructures through the progressive removal of residual organic species and the formation of oxygen vacancies or Zn-related defect [32].

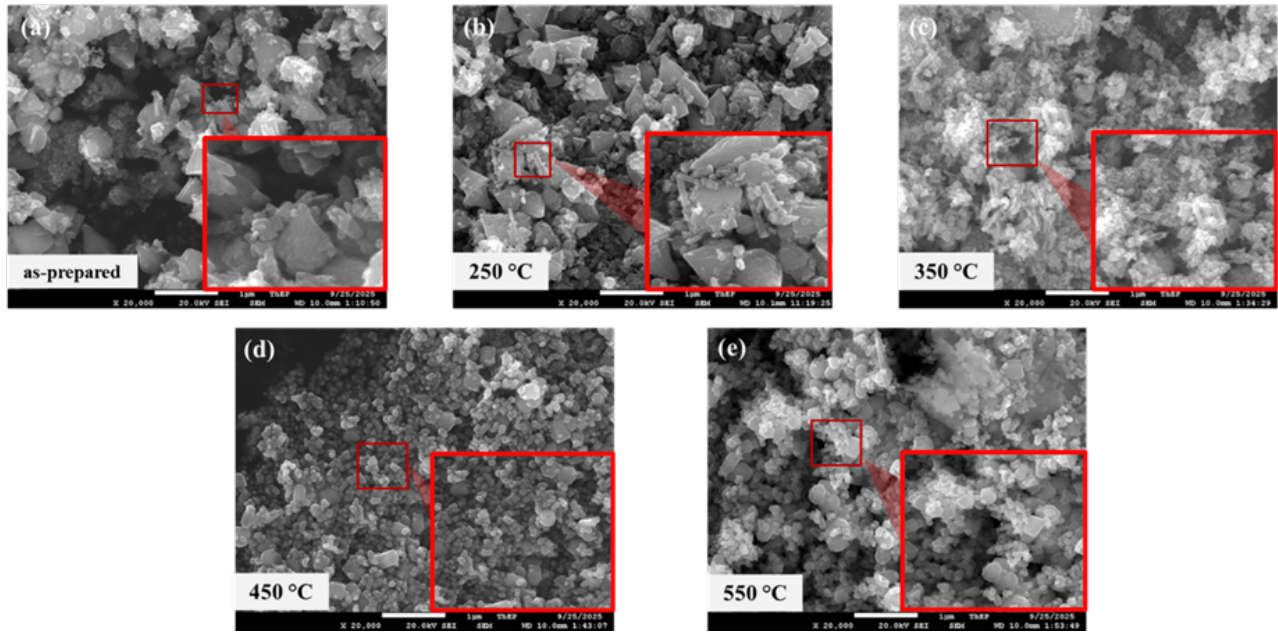


Fig. 1 FE-SEM micrographs of green-ZnO nanostructures with different calcination temperatures (a) as-prepared sample, and calcined at (b) 250 °C, (c) 350 °C, (d) 450 °C, and (e) 550 °C.

Table 2 Average particle size and Zn/O atomic ratio of ZnO nanostructures estimated from FE-SEM and EDS analyses at different calcination temperatures.

Conditions	Average particle size (nm)	Zn/O atomic ratio
as-prepared	381	0.65
250 °C	346	0.68
350 °C	83	1.49
450 °C	117	0.75
550 °C	156	1.06

The diffraction patterns of green ZnO nanostructures, as illustrated in Fig. 2, confirm that the calcined samples exhibit strong characteristic peaks of hexagonal wurtzite structure, indicating the formation of a crystalline ZnO phase. Distinct reflections observed at $2\theta = 31.8^\circ, 34.4^\circ, 36.3^\circ, 47.5^\circ, 56.6^\circ, 62.8^\circ, 66.4^\circ, 67.9^\circ, 69.1^\circ, \text{ and } 72.5^\circ$ are index to the 100, 002, 101, 012, 110, 013, 200, 112, 201, and 004 planes of hexagonal wurtzite (JCPDS no. 01-074-1331). In contrast, the sample without heat treatment presents several additional observed reflections at $2\theta = 11.8^\circ, 19.4^\circ, 24.2^\circ, \text{ and } 30.8^\circ$, which can be indexed to zinc acetate (JCPDS No: 00-001-0089) and indicate incomplete precursor decomposition. After calcination, the presence of the zinc acetate-related peaks is significantly decreased, suggesting partial decomposition of the zinc precursor and some residual organic compounds accompanied by the progressive development of ZnO crystallinity.

This observation is consistent with the FE-SEM results, which reveal the persistence of anisotropic morphologies at

lower calcination temperatures due to the presence of organic residues. Upon calcination at 450 °C and 550 °C, the diffraction peaks associated with the zinc acetate precursor are completely eliminated, and only the peaks of hexagonal wurtzite ZnO remain. These results indicate that highly crystalline ZnO is formed at elevated calcination temperatures, which is consistent with FE-SEM observations showing predominantly spherical particles under conditions where organic species are effectively removed. To further verify the decomposition of the zinc acetate precursor and the formation of ZnO, the relative intensity ratio between the dominant ZnO peak (I_{101}) and the zinc acetate peak (I_{ZA}) at approximately $2\theta \approx 19.5^\circ$ was evaluated. The ratio decreases significantly from 0.10 for the as-prepared sample to 0.01 for the sample calcined at 250 °C, indicating greater decomposition of the zinc acetate precursor during thermal treatment. At higher calcination temperatures (350 to 550 °C), the ratio becomes zero, confirming the complete removal of the zinc acetate phase.

The ZnO crystallite size was determined using the Debye–Scherrer’s equation [33] based on the dominant diffraction planes 100, 002, and 101. The calculated crystallite sizes range from 20 to 26 nm (Table 3), demonstrating that calcination temperature significantly influences crystallinity and structural refinement of the ZnO nanostructures. Based on SEM and XRD results, the green-ZnO nanostructures prepared using *Mitragyna speciosa* leaf extract exhibit characteristics comparable to the reports in previous studies. For example, ZnO nanoparticles synthesized via the chemical sol–gel route revealed a hexagonal wurtzite structure, with crystallite size increasing at higher calcination temperatures due to thermally driven grain growth, as reported by Kayani and the research group [31]. Similarly, Kahsay *et al.* reported green-synthesized hexagonal and triangular ZnO nanostructures using *Dolichos lablab* leaf extract, with an average crystallite size

of approximately 36 nm [34]. These results indicate that calcination temperature plays a crucial role in controlling crystallinity and crystallite growth. Meanwhile, the green synthesis process can produce diverse morphologies, depending on the reducing and capping properties of plant-derived phytochemicals. In the present study, a smaller crystallite size (approximately 20–26 nm) is attributed to the presence of phytochemicals from *Mitragyna speciosa*, which effectively limit crystal growth in the ZnO structure. This reduced crystallite size is advantageous, as it typically provides a higher specific surface area, promoting faster reaction kinetics in catalytic applications. However, a limitation of this work is the use of relatively mild calcination temperatures, which may result in incomplete removal of residual organic species or zinc salt precursor. This point can affect the phase purity and crystallinity compared to ZnO calcined at higher temperatures.

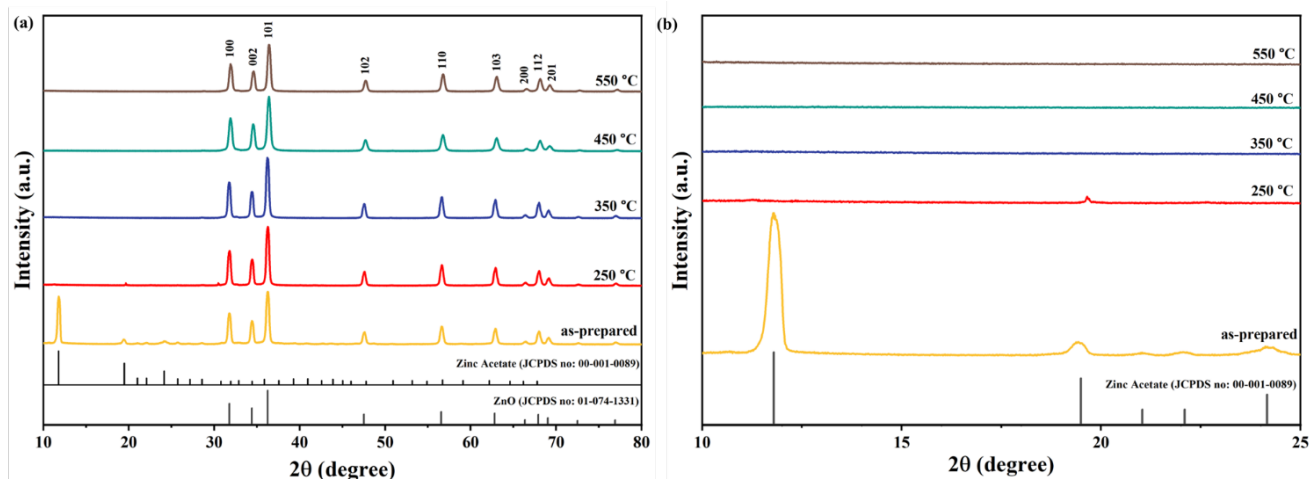


Fig. 2 (a) XRD patterns and (b) enlarged of ZnO nanostructures synthesized using plant extract as a function of calcination temperatures.

Table 3 Average crystallite sizes and intensity ratios of ZnO nanostructures estimated from XRD analysis under various calcination temperatures.

Conditions	Intensity ratio of I_{101}/I_{ZA}	Crystallite size (nm)
as-prepared	0.10	23 ± 0.39
250 °c	0.01	25 ± 2.57
350 °c	0	26 ± 3.98
450 °c	0	20 ± 0.58
550 °c	0	26 ± 3.68

The FTIR spectra of ZnO nanostructures and the extract of *Mitragyna speciosa* leaf are presented in Fig. 3. As shown in Fig. 3(a), several dominant absorption bands associated with the zinc acetate precursor and organic compounds originating from the *Mitragyna speciosa* leaf extract are observed in the as-prepared sample and the products under low calcined temperatures (250 to 350 °C).

Characteristic absorption bands at 620 and 690 cm^{-1} can be assigned to acetate anions in twisting and scissoring modes [35]. While both absorption bands around 1430 and 1540 cm^{-1} are associated with symmetric and antisymmetric stretching vibrations of COO^- group derived from zinc acetate [36]. In addition, the presence of phenolic compounds on ZnO surface is indicated by a band at

1025 cm^{-1} , corresponding to the C–O stretching vibration. These features confirm the presence of residual organic species and zinc acetate precursors in the low-temperature calcined samples. Meanwhile, a strong characteristic band in the range of 400–500 cm^{-1} , corresponding to Zn–O stretching vibration, is clearly observed in samples calcined at high temperature (450 and 550 $^{\circ}\text{C}$), confirming the formation of hexagonal wurtzite ZnO [37]. The disappearance of organic-related absorption bands at higher calcination temperatures indicates effective thermal decomposition of residual organic compounds and precursor species, consistent with the FE-SEM observations of morphological transformation and the XRD results confirming phase-pure ZnO formation. Meanwhile, FTIR

spectrum of the *Mitragyna speciosa* leaf extract (Fig. 3(b)) exhibits characteristic bands at approximately 1043 and 2985 cm^{-1} , which are assigned to C–O stretching vibrations of phenolic compounds and N–H stretching vibrations of amino acids, respectively [38]. These characteristic bands indicate the existence of phytochemicals, such as phenolics and amino acids, and contribute to nanoparticle formation by functioning as reducing and stabilizing species during nucleation and growth [39–41]. These findings collectively suggest that elevated calcination temperature accelerates phytochemical decomposition, leading to morphological transformation and enhanced ZnO phase purity, as confirmed by FTIR and XRD analyses.

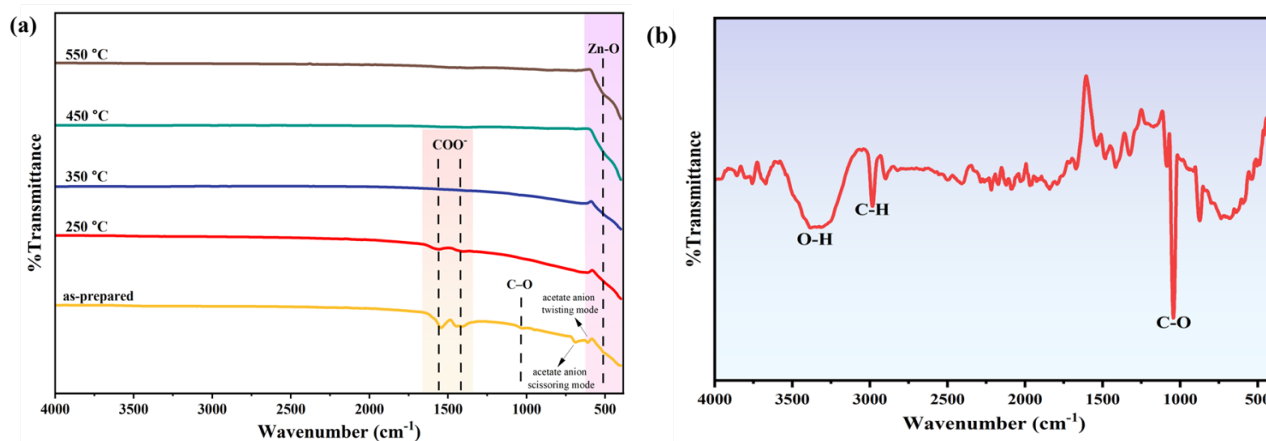


Fig. 3 FTIR spectra of (a) naturally derived ZnO nanostructures at different calcination temperatures and (b) *Mitragyna speciosa* leaf extract.

Nitrogen adsorption–desorption analysis was conducted to determine the specific surface area of ZnO nanostructures as a function of calcination temperature using the Brunauer–Emmett–Teller (BET) method, as shown in Fig. 4. According to the classification of IUPAC, all samples similarly exhibit a type IV isotherm, corresponding to mesoporous structures. BET surface area and average pore size diameter are summarized in Table 4. Specific surface area values of the as-prepared sample and ZnO calcined at 250, 350, 450, and 550 $^{\circ}\text{C}$ are determined to be 30.93, 37.32, 24.83, 31.40, and 22.25 $\text{m}^2 \text{g}^{-1}$, respectively. Therefore, calcination temperature plays a key role in tailoring the surface properties. The ZnO sample at 250 $^{\circ}\text{C}$ exhibits the highest specific surface area, accompanied by a relatively small average pore diameter of 5.86 nm. This behavior can be associated with the presence of anisotropic triangular-like and rod-like structures, as observed in the FE-SEM results. With further increases in the temperatures to 350 to 550 $^{\circ}\text{C}$, a general decrease in BET surface area related to an increase in average pore diameter is observed. This trend is attributed to agglomeration, thermal-induced particle growth, and partial pore collapse at higher calcination temperatures, which is consistent with the formation of the larger, more spherical particles observed in FESEM analysis. A high

specific surface area is expected to provide a great number of active sites for adsorption and surface reactions, which significantly enhance photocatalytic performance.

The photocatalytic and piezo-assisted photocatalytic performances of the naturally derived ZnO nanostructures with various temperatures were evaluated by Rhodamine B dye degradation, as depicted in Fig. 5. Among all samples, the as-prepared and ZnO calcined at 250 $^{\circ}\text{C}$ samples exhibit the highest photocatalytic efficiency under both conventional photocatalytic and piezo-assisted photocatalytic conditions, as shown in Fig. 5(a) and Fig. 5(b). This enhanced performance can be ascribed to the high surface area of these samples, which provides abundant active sites for surface adsorption. In addition, the superior photocatalytic activity of the sample calcined at 250 $^{\circ}\text{C}$ can be associated with the presence of residual phytochemical species on the ZnO surface, as confirmed by the FTIR result. These residual organics originating from the *Mitragyna speciosa* leaf extract may play a crucial role as surface modifiers, contributing to electron and hole (e^-/h^+) pair recombination, promoting the generation of reactive oxygen species (ROS), and providing additional adsorption sites for pollutant molecules as they do in the as-prepared sample without heat treatment. At calcination temperatures higher

than 250 °C, a decrease in photocatalytic performance is observed due to the progressive removal of residual organic species from the ZnO surface. The reduction in number of these surface-associated organic components may lead to fewer active sites and a diminished contribution to radical-

mediated reactions with the dye molecules. Thus, faster RhB degradation under photocatalytic reaction is observed for the as-prepared ZnO and the ZnO sample calcined at 250 °C compared to samples treated at higher calcination temperatures [42, 43].

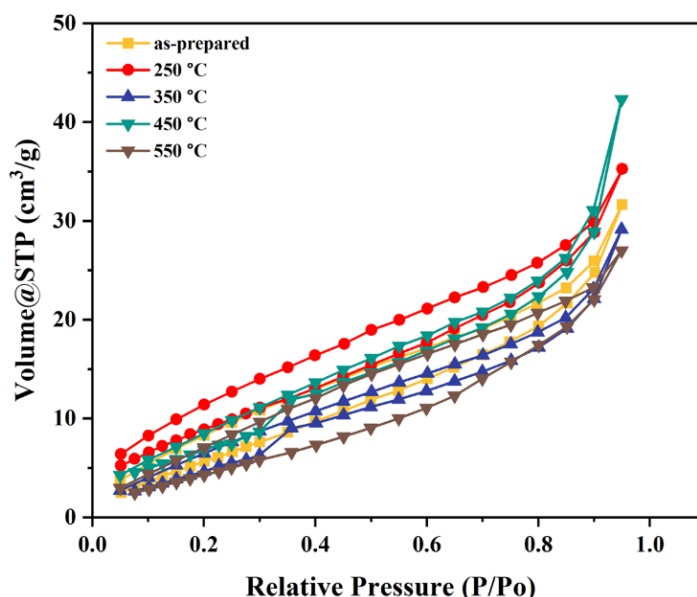


Fig. 4 N₂-isotherms and specific surface areas of green-ZnO nanostructures at different calcination temperature.

Furthermore, the incorporation of mechanical stimulation significantly enhances the photocatalytic performance due to the piezoelectric property of ZnO photocatalysts [44, 45]. Applied mechanical forces induce internal piezoelectric polarization charges, which facilitate more efficient separation of photogenerated charge carriers, thereby reducing charge recombination and enhancing ROS generation. Accordingly, the photo-driven catalysis behavior of ZnO nanostructures is remarkably improved under combined light activation and mechanical excitation. As schematically illustrated in Fig. 5(c), the photodegradation mechanism of ZnO nanostructures derived by the green process is initiated with UV light irradiation. Upon light irradiation, electrons in the valence

band (VB) are excited to the conduction band (CB), generating electron and hole pairs. After that, superoxide radicals ($\bullet\text{O}_2^-$) are generated by the reaction of excited electrons (e^-) with oxygen (O_2) molecules. While the presence of hydroxyl radicals ($\bullet\text{OH}$) is produced by the reduction of photogenerated holes (h^+) and H_2O [34]. Additionally, photocatalytic activity can be improved by residual organic species on the ZnO surface, which modify surface chemistry and increase the number of active adsorption and catalytic sites. This modification facilitates the formation of reactive oxygen species, which subsequently oxidize and decompose RhB dye molecules and other organic pollutants [46, 47].

Table 4 Specific surface area and average pore diameter of green-synthesized ZnO nanostructures calcined at different temperatures

Conditions	Specific surface area ($\text{m}^2 \text{g}^{-1}$)	Average pore diameter (nm)
as-prepared	30.93	6.35
250 °c	37.32	5.86
350 °c	24.83	7.28
450 °c	31.40	8.35
550 °c	22.25	7.50

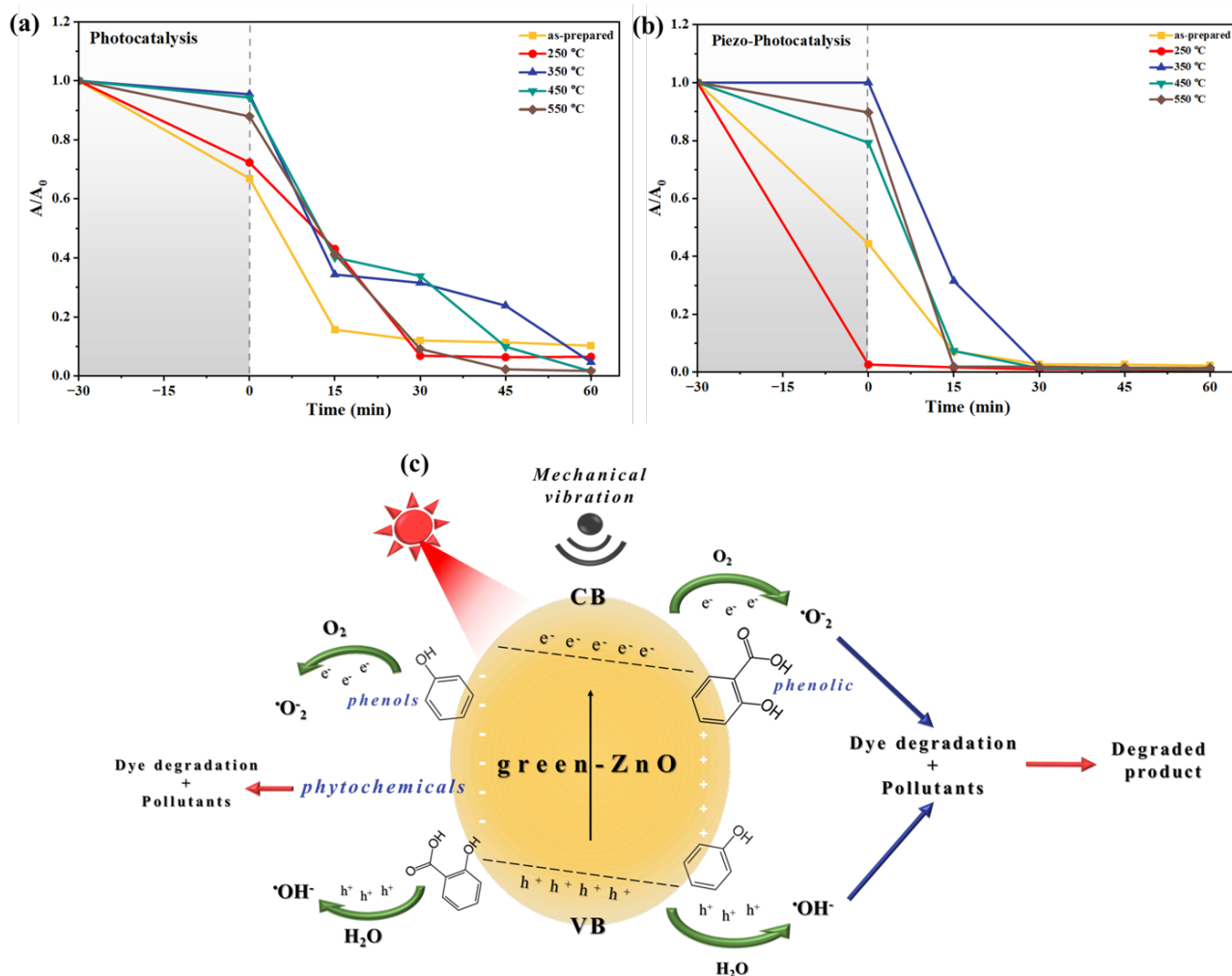


Fig. 5 Photocatalytic activities of green-ZnO nanostructures at different calcination temperatures: (a) photocatalytic performance, (b) piezo-photocatalytic activity, and (c) photocatalytic mechanisms of ZnO nanostructures.

4. Conclusion

Green synthesis using *Mitragyna speciosa* Korth. leaf extract successfully produced ZnO nanostructures, offering an environmentally friendly and sustainable alternative to conventional chemical synthesis routes. The calcination temperature was found to play a crucial role in governing the crystallinity, morphology, stoichiometric composition, defect structure, and specific surface area of the ZnO nanostructures. Increasing the calcination temperature enhanced ZnO crystalline and phase purity, induced a transformation in particle morphology, and reduced the specific surface area due to particle growth and agglomeration. In both conventional photocatalytic and piezo-assisted photocatalytic systems, the as-prepared and the ZnO sample at 250 °C showed superior photocatalytic performance, which was attributable to their higher specific surface area and residual organic species derived from the leaf extract. These surface-associated organic components are suggested to act as active surface modifiers, improving adsorption capacity and facilitating catalytic reactions by promoting reactive species generation. Consequently, the

synergistic effects of surface chemistry, morphology, and piezoelectric-assisted charge separation contribute to the improved photocatalytic efficiency of the green-synthesized ZnO nanostructures.

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6. Declaration of Generative AI in Scientific Writing

An Artificial Intelligence (AI) tool was used solely for checking and improving the grammatical correctness of the language.

7. CRediT Author Statement

Thanyapa Sanyen: Writing Original Draft; Conceptualization; Methodology; Software; Data Curation.
Maneerat Songpanit: Conceptualization; Investigation.
Thanaphon Kansaard: Investigation; Validation.
Sutee Chutipaijit: Methodology; Investigation; Supervision.
Kanokthip Boonyarattanakalin: Investigation; Supervision; Formal analysis; Validation.
Wisanu Pecharapa: Investigation; Supervision; Visualization.
Wanichaya Mekprasart: Conceptualization; Investigation; Project administration; Supervision; Funding acquisition; Writing - Review & Editing.

8. Research Involving Human and Animals Rights

Not applicable

9. Ethics Approval and Consent to Participate

Not applicable

10. Declaration of Competing Interest

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

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