MRS Advances (2026) 11:750–755
https://doi.org/10.1557/s43580-026-01623-6

ORIGINAL PAPER

Effect of *Cynara scolymus* extract concentration on the synthesis of ZnO semiconductor nanoparticles and their photocatalytic performance in the degradation of Rhodamine B, Methylene Blue, Methyl Red, Methyl Orange, Amino Black, and Alizarin Yellow

Priscy Alfredo Luque Morales[1]

Received: 30 September 2025 / Accepted: 17 March 2026 / Published online: 25 March 2026
© The Author(s) 2026

Abstract

Zinc oxide nanoparticles were synthesized through a green chemistry route using *Cynara scolymus* extract. FTIR spectra confirmed Zn–O stretching vibrations along with residual organic functional groups from the extract. UV–Vis analysis indicated band gap energies ranging from 2.87 to 2.95 eV, confirming the semiconductor behavior of ZnO. XRD analysis revealed the hexagonal wurtzite phase with crystallite sizes decreasing from 53.1 to 36.3 nm as extract concentration increased. SEM micrographs revealed aggregated ZnO nanoparticles forming irregular clusters with rough surface morphology, a feature commonly observed in plant-mediated green synthesis. Photocatalytic performance was evaluated against six dyes: Rhodamine B, Methylene Blue, Methyl Red, Methyl Orange, Amino Black, and Alizarin Yellow. The ZnO sample synthesized with 5% extract exhibited the highest degradation efficiency, achieving > 90% degradation of Rhodamine B and Amino Black. These findings demonstrate the potential of *C. scolymus* mediated ZnO NPs for sustainable wastewater treatment applications.

Introduction

Nanoparticles (NPs) with dimensions between 1 and 100 nm, act as a bridge between bulk materials and molecular or atomic structures. These particles exhibit unique properties derived from their reduced size, high surface area to volume ratio, free surface bonds, and high reactivity, distinguishing them from conventional materials [1]. Currently, scientific interest has focused on various strategies for nanoparticle synthesis through chemical, physical, and biological routes. These methods allow the production of high purity nanomaterials with controlled morphology, although they often involve high energy consumption and extreme pressure and temperature conditions. Laser ablation in liquids stands out for producing nanoparticles [2]. Another widely applied approach is high energy ball milling [3]. Likewise, cathodic sputtering deposition has been consolidated as a versatile technique [4]. Other methods, such as physical vapor deposition (PVD), ultrasonic spray pyrolysis, and electric arc, are also employed [5, 6]. In contrast to conventional physical and chemical methods, the present work employs a green synthesis route using *Cynara scolymus* extract as a reducing and stabilizing agent for the preparation of ZnO nanoparticles. This approach reduces the use of toxic reagents and harsh reaction conditions, aligning with the principles of environmental sustainability. Water pollution has become one of the most significant environmental challenges today due to the continuous release of industrial effluents that contain dyes, pharmaceuticals, and other hazardous organic compounds. Traditional treatment methods are often ineffective or produce secondary pollutants, which limits their sustainability [7]. In this context, heterogeneous photocatalysis has emerged as a promising and ecofriendly approach for degrading persistent contaminants using light irradiation [8]. Among various photocatalysts, ZnO-based nanomaterials have garnered considerable attention due to their stability, low cost, and high photocatalytic efficiency. ZnO is an n-type wide band gap semiconductor with a high exciton binding energy (60 meV) and relatively high electron mobility compared with other semiconductor oxides. These properties favor the efficient generation and separation of electron–hole pairs under UV irradiation,

✉ Priscy Alfredo Luque Morales
pluque@uabc.edu.mx

[1] Facultad de Ingeniería, Arquitectura y Diseño-Universidad Autónoma de Baja California, Carr. Transpeninsular 3917, C.P. 22860 Ensenada, Baja California, Mexico

thereby enhancing photocatalytic oxidation processes [9]. Recent advances in green synthesis strategies have further improved their applicability in wastewater treatment [10, 11]. Green synthesis utilizes biological compounds as reducing and stabilizing agents. In the case of zinc oxide (ZnO), this material has become one of the most attractive options due to its low cost, ease of production, and well known antimicrobial properties [12, 13]. The present work aims at the green synthesis of ZnO semiconductor nanoparticles using natural *C. scolymus* extract, in order to evaluate their effectiveness in the photocatalytic degradation of six model dyes: Rhodamine B (RhB), Methylene Blue (MB), Methyl Red (MR), Methyl Orange (MO), Amino Black (AB), and Alizarin Yellow (AY).

Materials and methods

Materials

An extract of *C. scolymus* and zinc nitrate $(Zn(NO_3)_2)\cdot 6H_2O$ were used in the green synthesis of ZnO nanoparticles. Six organic dyes, commonly employed as model contaminants, were selected for the study: Methylene Blue (MB), Methyl Orange (MO), Rhodamine B (RhB), Methyl Red (MR), Amino Black (AB), and Alizarin Yellow (AY).

Synthesis of ZnO nanoparticles

Fresh leaves of *C. scolymus* were used as the plant material. The leaves were washed with distilled water and cut into small fragments. Aqueous extracts were prepared at concentrations of 1%, 3%, and 5% (w/v), corresponding to 0.5, 1.5, and 2.5 g of plant material in 50 mL of deionized water, respectively. The mixtures were subjected to magnetic stirring for 2 h at room temperature, followed by heating in a water bath at 60 °C for 1 h. The solutions were then filtered to obtain the extracts. Subsequently, 2 g of $Zn(NO_3)_2\cdot 6H_2O$ were added to each extract, and the mixture was stirred for 1 h prior to calcination at 400 °C for 1 h to obtain ZnO nanoparticles. The samples were labeled based on the concentration of the *C. scolymus* extract used: ZnO–Cs-1% for 1%, ZnO–Cs-3% for 3%, and ZnO–Cs-5% for 5%.

Photocatalytic activity

A total of 50 mg of ZnO nanoparticles were used in 50 mL of aqueous solutions containing six dyes: Methylene Blue (MB), Methyl Orange (MO), Rhodamine B (RhB), Methyl Red (MR), Amino Black (AB), and Alizarin Yellow (AY). The mixtures were stirred in the dark for 30 min and then irradiated with UV light. Every 10 min for a total irradiation time of 180 min, 2 mL aliquots were withdrawn and analyzed using UV–Vis spectrophotometry.

Results and discussion

FTIR

Figure 1 shows the FTIR spectra of the pure *C. scolymus* extract and the ZnO nanoparticles synthesized with 1%, 3%, and 5% extract concentrations. The spectrum corresponding to the pure *C. scolymus* extract (gray line in Fig. 1) exhibits a broad band in the 3200–3600 cm^{-1} region corresponding to O–H stretching vibrations of hydroxyl and phenolic groups, as well as signals in the 1600–1700 cm^{-1} and 1000–1300 cm^{-1} regions associated with C=O, C=C, and C–O functional groups. In the ZnO samples, these bands decrease in intensity, indicating that residual organic compounds from the extract remain adsorbed on the nanoparticle surface. The intense band observed in the 400–600 cm^{-1} region is attributed to Zn–O stretching vibrations characteristic of the hexagonal wurtzite structure of ZnO. The slight variations in intensity with extract concentration may be related to differences in crystallinity and surface structure. These findings are consistent with previous reports on green synthesized ZnO [14].

UV–Vis and SEM

Figure 2a–f illustrates the optical and morphological characterization of ZnO synthesized using *C. scolymus* extract at various concentrations (1%, 3%, and 5%). The optical band gap of the synthesized ZnO samples was estimated from

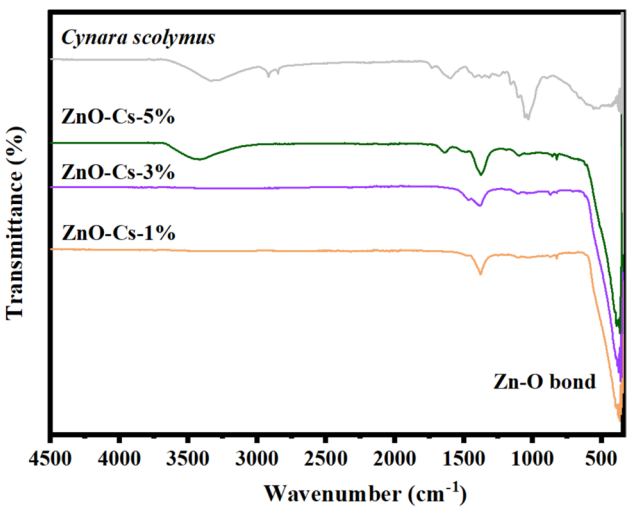


Fig. 1 FTIR spectra of ZnO synthesized with *C. scolymus* extract (1%, 3%, and 5%)

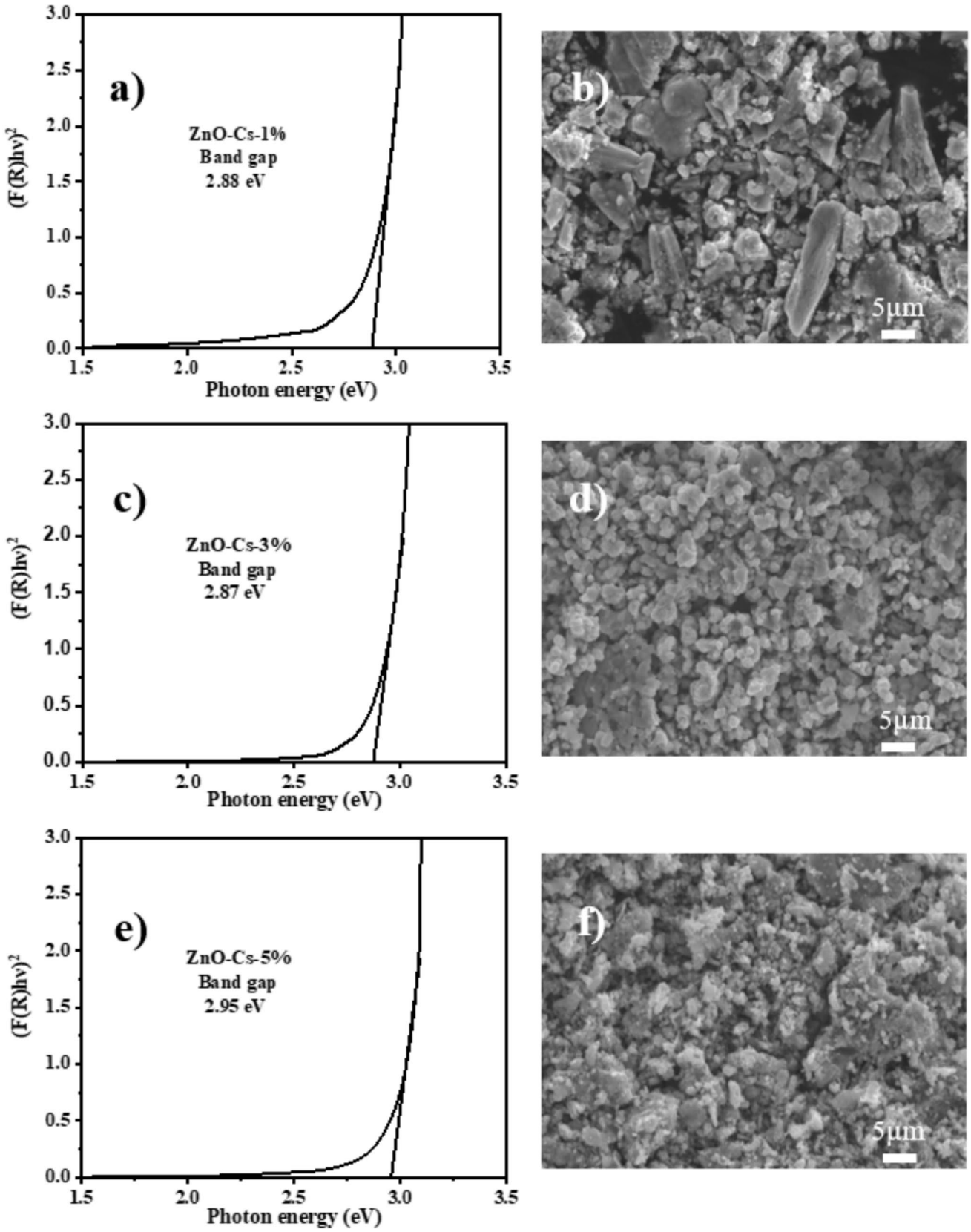


Fig. 2 UV–Vis spectra (**a**, **c**, **e**) and SEM micrographs (**b**, **d**, **f**) of ZnO nanoparticles synthesized using *C. scolymus* extract at concentrations of 1% (**a**, **b**), 3% (**c**, **d**), and 5% (**e**, **f**)

diffuse reflectance UV–Vis spectra using the Kubelka–Munk method, as shown in Fig. 2a, c, e. By extrapolating the linear region of the plots to the photon energy axis, the band gap values were determined to be 2.88 eV for ZnO–Cs-1%, 2.87 eV for ZnO–Cs-3%, and 2.95 eV for ZnO–Cs-5%. The slight reduction compared with bulk ZnO may be attributed to size effects and surface defects [15, 16]. The SEM micrographs shown in Fig. 2b, d, f reveal aggregated particles forming irregular clusters with rough surface morphology. The observed agglomeration is commonly reported in ZnO nanoparticles synthesized using plant extracts, where phytochemicals act as nucleation, stabilization, and capping agents during particle growth [17].

Figure 3 illustrates the XRD patterns of ZnO obtained using *C. scolymus* extract at concentrations of 1%, 3%, and 5%. These patterns display characteristic peaks associated with the wurtzite phase of ZnO, which are indexed as (100), (002), (101), (102), (110), (103), (200), (112), and (201). This is consistent with the JCPDS reference pattern 36-1451. The sharp and intense peaks indicate good crystallinity. Additionally, the estimated crystallite size, calculated using the Debye–Scherrer equation:

$$D = \frac{K\lambda}{\beta cos\theta},$$

where D is the crystallite size, K is the shape factor (0.9), λ is the X-ray wavelength (Cu Kα radiation, 0.15406 nm), β is the full width at half maximum (FWHM) of the (101) diffraction peak expressed in radians, and θ is the Bragg angle. The crystallite size decreases as the extract concentration increases: 53.1 nm at 1%, 45.3 nm at 3%, and 36.3 nm at 5%. This suggests that the metabolites in the extract enhance nucleation and restrict crystal growth [18, 19].

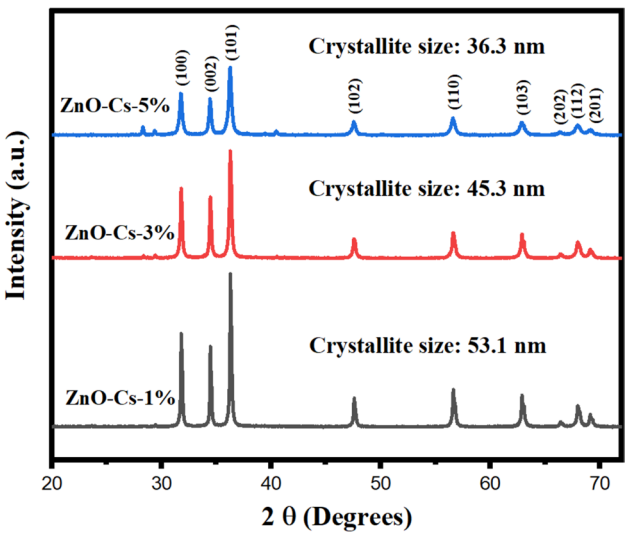


Fig. 3 XRD patterns of ZnO synthesized with *C. scolymus* extract (1%, 3%, and 5%) with calculated crystallite sizes

Photocatalytic activity

Figure 4a–f illustrates the photocatalytic efficiency of ZnO nanoparticles synthesized using *C. scolymus* extract at different concentrations (1%, 3%, and 5%) for the degradation of six model organic dyes: Rhodamine B (a), Methylene Blue (b), Methyl Red (c), Methyl Orange (d), Amino Black (e), and Alizarin Yellow (f). In all cases, a progressive decrease in dye concentration is observed under UV irradiation over 180 min, following an initial adsorption phase in the dark to ensure surface-dye equilibrium. Photolysis experiments were also performed for all dyes under the same irradiation conditions in the absence of the photocatalyst to evaluate the contribution of light alone to the degradation process. The results indicate that increasing the concentration of the plant extract during synthesis significantly impacts photocatalytic activity. Specifically, the material with 5% extract exhibits the highest efficiency in degrading Rhodamine B and Amino Black. In contrast, the samples with 1% and 3% extract show slower degradation kinetics. An intermediate behavior is observed for Methylene Blue, Methyl Red, and Methyl Orange, toward higher efficiency as the extract concentration increases, promoting smaller crystallite sizes and consequently enhancing electron–hole pair generation. However, for Alizarin Yellow, all three concentrations exhibit lower photodegradation rates. This may be attributed to the dye's structural complexity and the resistance of chromophoric groups toward oxidation. These findings align with recent reports indicating that ZnO obtained through green synthesis demonstrates variations in dye degradation kinetics influenced by the preparation method, morphology, and residual metabolites from the extract that may serve as additional active sites or partial inhibitors [20–23].

Conclusion

The ZnO nanoparticles synthesized using *C. scolymus* extract demonstrated the successful formation of the material, evidenced by the characteristic Zn–O vibration band in FTIR spectra. Scanning electron microscopy (SEM) revealed that the particles formed aggregates with a rough morphology. Additionally, UV–Vis spectroscopy indicated band gap values ranging from 2.87 to 2.95 eV, which is typical of nanocrystalline materials. X-ray diffraction (XRD) patterns confirmed the presence of the pure wurtzite phase and showed a progressive decrease in crystallite size, from 53.1 to 36.3 nm, as the concentration of the extract increased. In photocatalytic tests, all three samples effectively degraded six different dyes, with the

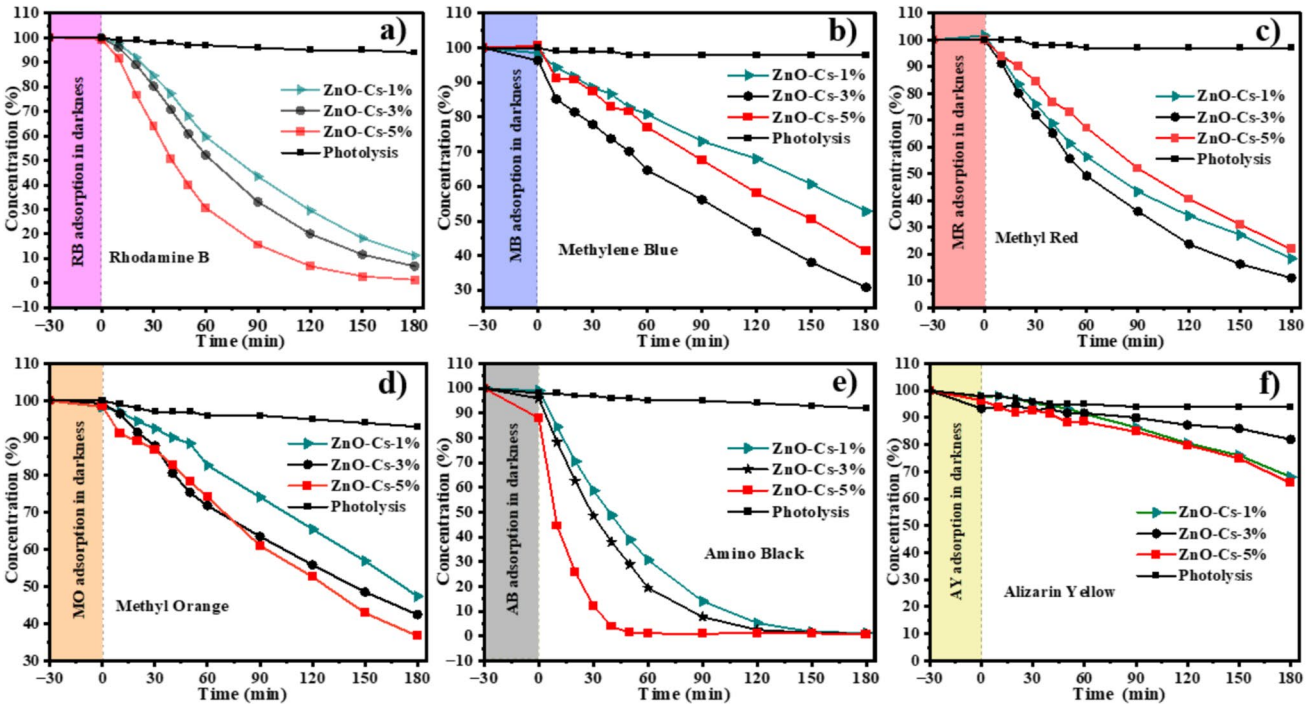


Fig. 4 Photocatalytic degradation of Rhodamine B (RhB), Methylene Blue (MB), Methyl Red (MR), Methyl Orange (MO), Amino Black (AB), and Alizarin Yellow (AY) using ZnO synthesized with *C. scolymus* extract (1%, 3%, and 5%)

5% concentration exhibiting the highest efficiency. These findings highlight the potential of using *C. scolymus* as a green approach for synthesizing ZnO with improved optical and photocatalytic properties, making it a promising solution for the degradation of pollutants in water.

Acknowledgments The authors would like to acknowledge the support received from projects 402/3391 and 402/3751 at the Autonomous University of Baja California (UABC), as well as project 402/1/C/58/24. Daniel Perez for his contributions in the materials biosynthesis laboratory. This research was funded by the Frontera Science Project, grant number CF-2023-I-1805, from CONACYT.

Author contributions P.A. Luque: conceptualization, investigation, visualization, data curation, writing original draft.

Funding This study was supported by Conacyt (Grant No. CF-2023-I-1805).

Data availability The data may be available upon request from the author.

Declarations

Conflict of interest The author declares that there are no conflicts of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. I. Hussain, N.B. Singh, A. Singh, H. Singh, S.C. Singh, Green synthesis of nanoparticles and its potential application. Biotechnol. Lett. **38**, 545–560 (2015). https://doi.org/10.1007/s10529-015-2026-7
2. W. Shaheen et al., Laser ablation in liquids: versatile technique for nanomaterials synthesis. Surf. Sci. Rep. **80**, 100661 (2025). https://doi.org/10.1016/j.surfrep.2025.100661
3. C. Suryanarayana, Mechanical milling: a superior nanotechnological tool for the synthesis of advanced nanomaterials. Nanomaterials **11**, 2682 (2021). https://doi.org/10.3390/nano11102682

4. T.H. Nguyen et al., Sputter deposition onto liquids: controlling nanoparticle size, composition and morphology. Soft Matter **18**, 655–672 (2022). https://doi.org/10.1039/D1SM01002F
5. A. Chauhan et al., Physical synthesis of metallic nanoparticles: techniques and applications. Mater. Today Chem. **30**, 101343 (2023). https://doi.org/10.1016/j.mtchem.2023.101343
6. L. Yang et al., Ultrasonic spray pyrolysis for functional nanomaterials: recent progress and applications. Adv. Powder Technol. **34**, 106983 (2023). https://doi.org/10.1016/j.apt.2023.106983
7. S. Ahmed, M.G. Rasul, R. Brown, M.A. Hashib, Influence of parameters on the heterogeneous photocatalytic degradation of pesticides and phenolic contaminants in wastewater: a short review. J. Environ. Manage. **92**, 311–330 (2011). https://doi.org/10.1016/j.jenvman.2010.08.016
8. A. Fujishima, X. Zhang, D.A. Tryk, TiO_2 photocatalysis and related surface phenomena. Surf. Sci. Rep. **63**, 515–582 (2008). https://doi.org/10.1016/j.surfrep.2008.10.001
9. Ü. Özgür, Y.I. Alivov, C. Liu, A. Teke, M.A. Reshchikov, S. Doğan, V. Avrutin, S.-J. Cho, H. Morkoç, A comprehensive review of ZnO materials and devices. J. Appl. Phys. **98**, 041301 (2005). https://doi.org/10.1063/1.1992666
10. J. Low, S. Cao, J. Yu, S. Wageh, Semiconductor-Based photocatalytic water purification: materials, mechanisms, and applications. Nanomaterials **10**, 1120 (2020). https://doi.org/10.3390/nano10061120
11. M.A. Ahmed, R.S. Kershi, A.A. Al-Ghamdi, Recent progress in ZnO-based photocatalysts for environmental remediation under visible light. Catalysts **12**, 635 (2022). https://doi.org/10.3390/catal12060635
12. H. Agarwal, S.V. Kumar, S. Rajeshkumar, A review on green synthesis of zinc oxide nanoparticles – an eco-friendly approach. Resour.-Effic. Technol. **3**, 406–413 (2017). https://doi.org/10.1016/j.reffit.2017.03.002
13. M. Sundrarajan, S. Ambika, K. Bharathi, Plant-extract mediated synthesis of ZnO nanoparticles using *Pongamia pinnata* and their activity against pathogenic bacteria. Adv. Powder Technol. **26**, 1294–1299 (2015). https://doi.org/10.1016/j.apt.2015.07.001
14. J. Singh, T. Dutta, K. Kim, M. Rawat, P. Samddar, P. Kumar, Green synthesis of zinc oxide nanoparticles using plant extracts and their environmental applications: a review. Appl. Phys. A **127**, 418 (2021). https://doi.org/10.1007/s00339-021-04915-w
15. S. Srikant, D.R. Clarke, On the optical band gap of zinc oxide. J. Appl. Phys. **83**, 5447–5451 (1998). https://doi.org/10.1063/1.367375
16. A.B. Djurišić, Y.H. Leung, Optical properties of ZnO nanostructures. Small **2**, 944–961 (2006). https://doi.org/10.1002/smll.200600134
17. A. Kołodziejczak-Radzimska, T. Jesionowski, Zinc oxide—from synthesis to application: a review. Materials **7**, 2833–2881 (2014). https://doi.org/10.3390/ma7042833
18. P. Perumal, P. Velu, S. Muthukumaran, A.B.H. Susan, Green synthesis of zinc oxide nanoparticles using aqueous plant extract and their potential biomedical applications. Sci. Rep. **14**, 2797 (2024). https://doi.org/10.1038/s41598-024-52217-x
19. G.G. di Confiengo, M.S. Bernardo, A.R. Landa-Cánovas, J.M. de la Fuente, M.L. López-Quintela, A sustainable way to produce ZnO nanoparticles with tunable properties. Mater. Chem. Phys. **317**, 128766 (2024). https://doi.org/10.1016/j.matchemphys.2024.128766
20. A.A. Ansari, M.M. Khan, M.H. Cho, Green synthesis of ZnO nanostructures and their applications for photocatalytic dye degradation. J. Environ. Chem. Eng. **12**, 114241 (2024). https://doi.org/10.1016/j.jece.2024.114241
21. L. Zhang, Y. Wang, H. Yu, J. Li, Enhanced photocatalytic performance of ZnO nanoparticles synthesized via green routes for organic dye degradation. Chemosphere **348**, 140528 (2024). https://doi.org/10.1016/j.chemosphere.2023.140528
22. R. Ahmed, A. Gul, S. Shah, Eco-friendly synthesis of ZnO nanoparticles for wastewater treatment: photocatalytic and antibacterial activities. J. Photochem. Photobiol. A Chem. **457**, 114561 (2024). https://doi.org/10.1016/j.jphotochem.2024.114561
23. D. Morales, M. Torres, J.C. Martínez, Photocatalytic degradation of synthetic dyes using plant-extract mediated ZnO nanostructures. Sep. Purif. Technol. **326**, 125303 (2024). https://doi.org/10.1016/j.seppur.2024.125303

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.