

Toward Sustainable Photocatalysis—Insights on Green-Synthesized ZnO Nanoparticles for Ciprofloxacin Degradation

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Introduction

The upsurge in world population has placed an active demand on the quest for a good life and industrialization. This has also resulted in the continual discharge of pollutants, which include heavy metals, cosmetic products, fertilizers, pesticides, pharmaceutical wastes, dyes, etc., into the available water bodies through various anthropogenic activities [1–5]. Furthermore, the continual increase in the above-mentioned pollutants vis-à-vis pharmaceutical contaminants in the aquatic ecosystem is a call for concern. This, therefore, necessitates the development of durable, sustainable and multifunctional solutions. In this context, the study by Bamisaye *et al.* [6], titled “*Synthesis of zinc oxide nanoparticles using Syzygium malaccense leaf extract: Photocatalytic decomposition of ciprofloxacin and antimicrobial studies*”, is a timely and innovative advancement. The research entails the adoption of an eco-friendly technique, which is the green synthetic route for the production of zinc oxide (ZnO) nanoparticles using *Syzygium malaccense* leaf extract. Thus, serving a dual purpose which include the degradation of antibiotics and microbial inhibition. This eco-conscious approach is in synchrony with global efforts to minimize chemical toxicity and energy consumption in nanomaterial synthesis.

Metal oxide nanoparticles or nanocatalysts have attracted a lot of attention in recent times due to their less toxic and biopotency characteristics [7,8]. The particles are known for their strong antibacterial properties and their ability to break down pollutants when exposed to light [2,9,10]. One of their

major applications is in photo catalysis, which has been widely studied for removing antibiotic residues from the environment. Among these, zinc oxide (ZnO) nanoparticles have emerged as one of the valuable and important metal oxides, due to their inherent properties to efficiently degrade various organic pollutants into harmless substances when exposed to UV or visible light [11–13]. Moreover, ZnO nanoparticles also show strong antibacterial effects against both Gram-positive and Gram-negative bacteria [6,14]. Due to these properties, they are being studied for various medical and environmental applications, which include water treatment systems, food packaging, medical tools, and drug delivery. In addition, they also act as antioxidants and have shown potential for anti-cancer and anti-inflammatory treatments [15].

The main goal of the study is the adoption of green chemistry method as a safer and more eco-friendly alternative to traditional chemical synthesis. Which necessitated the study, aimed at the synthesis of ZnO nanoparticles using leaf extracts from *Syzygium malaccense*, its tendency to effectively break down ciprofloxacin, and the determination of its biopotency against disease-causing pathogens.

The aim is to support the development of eco-friendly, multi-purpose nanomaterials by combining green nanotechnology with environmental and biomedical research. As such, this commentary provides an insight into the scientific merit, technical depth, and far-reaching impacts of the study, giving its contributions to nanotechnology, water treatment, and sustainable material science. It also helps to open up the probable areas for future enhancement in such a way as to fully maximize real-world applications.

Summary of the Article

The study presents a biogenic approach for synthesizing ZnO nanoparticles using *Syzygium malaccense* leaf extract as a capping and reducing agent due to the rich presence of phytochemicals. The synthesized nanoparticles were characterized using UV–Vis spectroscopy, FTIR, XRD, SEM, and EDX, confirming a band gap of 3.23 eV and a crystalline face-centered cubic (FCC) structure. The ZnO nanoparticles recorded an optimum degradation efficiency of 88.10% for ciprofloxacin under UV light, following pseudo-first-order kinetics. Moreover, MIC values ranging from 10–50 mg/mL against five clinically relevant bacteria strains show the biopotency efficiency of the materials. These findings underscore the dual utility of the synthesized ZnO NPs for both environmental and biomedical applications.

Scientific Merits and Strengths

This study shows a strong scientific merit through the innovative adoption of *Syzygium malaccense* plant extract for the synthesis of ZnO nanoparticles, offering a sustainable alternative to conventional methods. Its dual functionality in degrading ciprofloxacin and inhibiting bacterial growth highlights multidisciplinary relevance. Employing robust characterization techniques and kinetic modelling, the research substantiates the photocatalytic applicability while contributing significantly to the advancement of eco-friendly nanomaterials for environmental and biomedical applications.

Green synthesis innovation

The utilization of *Syzygium malaccense* extract in the synthesis of ZnO nanoparticles exemplifies a credible, eco-benign alternative to conventional chemical synthetic routes. Rich in bioactive compounds such as flavonoids, tannins, and phenolics, the plant extract acts simultaneously as a reducing and stabilizing agent [17]. This green approach reduces the need for the use of hazardous chemicals, low energy consumption, and minimized adverse environmental impact, which is in alignment with the 12 Principles of Green Chemistry [18,19]. *Syzygium malaccense* leaves were cleaned, dried, powdered, and boiled in water to prepare an extract. This extract was combined with zinc sulphate and stirred at 80°C for 4 hours to synthesize ZnO nanoparticles, followed by centrifugation, washing, drying, and annealing [20,21]. Characterization was done using UV–Vis, FTIR, XRD, and SEM–EDX to analyze optical, structural, and elemental properties. Photocatalytic degradation of ciprofloxacin was assessed under UV light, and kinetics analyzed using a pseudo-first-order model. Antibacterial efficacy was tested via broth dilution and plating methods. MIC and MBC were determined, and statistical analysis was performed using GraphPad Prism and OriginPro.

Multidomain relevance

The study's multidomain relevance lies in its successful integration of material science, analytical chemistry, environmental nanotechnology and microbiological or biomedical applications. These were achieved through the green synthesis of ZnO nanoparticles and the demonstration of their efficacy in degrading ciprofloxacin, which has been classified as a persistent pharmaceutical pollutant. The study addresses a pressing challenge in water purification. Simultaneously, the nanoparticles exhibit significant antimicrobial activity against clinically relevant pathogens, offering potential for biomedical applications. This dual functionality underscores the versatility of biogenic ZnO nanomaterials and positions them as promising candidates for interdisciplinary solutions. The research effectively bridges material science, environmental engineering, and microbiology, thus advancing holistic strategies for pollution control and public health menace mitigation.

Robust analytical framework

The study is supported by a robust analytical framework, utilizing a comprehensive characterization technique to validate the physicochemical and functional properties of the synthesized ZnO nanoparticles. UV–Vis spectroscopy shows the optical activity with the bandgap energy, while FTIR elucidated surface functional groups, recording a successful bio-reduction and stabilization. The XRD analysis provides an insight into the crystallinity and phase purity, while the morphology and elemental composition of the biogenically synthesized material were elucidated using SEM and EDX. Kinetic modelling of the ciprofloxacin degradation process further substantiated the photocatalytic mechanism. The comprehensive analytical strategy not only reinforces the reliability of the findings but also enhances the reproducibility and scientific credibility of the research.

Critical Reflections

It is clear that the study is technically rigorous and environmentally impactful, with the findings of the study showing that the green-synthesized ZnO nanoparticles exhibited a strong UV–Vis absorption peak at 371 nm and an optical band gap of 3.23 eV. FTIR spectra confirmed functional groups at 574 cm⁻¹ (Zn–O), 1033 cm⁻¹ (Zn–O–Zn), 1188 cm⁻¹ (C–O), and 1643 cm⁻¹ (C=C). XRD analysis revealed a face-centered cubic (FCC) structure with a dominant peak at $2\theta = 26.55^\circ$ and an average crystallite size of 24.73 ± 2.90 nm [6]. SEM showed a heterogeneous morphology, while EDX indicated elemental composition of Zn (27.6%) and O (61.08%). Photocatalytic degradation of 10 ppm ciprofloxacin achieved 88.10% removal in 80 min using 0.4 g ZnO NPs, following pseudo-first-order kinetics with a rate constant, $k = 0.0133 \text{ min}^{-1}$. MIC values ranged from $10 \pm 0.6 \text{ mg/mL}$

(*Enterobacter* spp) to 50 ± 3.0 mg/mL (*E. cloacae*), while MBC ranged from 64 to 75 mg/mL, indicating both bactericidal and bacteriostatic effects depending on the organism. However, several critical aspects need further investigation. First, the limited visible-light response of ZnO nanoparticles remains a challenge; it is imperative to conduct the study under visible or natural sunlight, but this could be limited due to the wide band gap value. Forming a composite or heterojunction with other semiconductors with a narrow bandgap will narrow the wide bandgap of the material, ZnO nanoparticles. This could significantly improve solar-driven applications. Secondly, the study did not assess the environmental toxicity of the material, and as such does not address the potential ecotoxicological impacts of ZnO nanoparticles in aquatic ecosystems, which is vital for determining the environmental safety. Finally, the selective antimicrobial mechanism remains underexplored. Employing advanced proteomic or genomic techniques could unravel the molecular basis of the microbial inhibition as reported by Khosrovyan *et al.* [22], thereby enabling the design of more targeted and efficient antimicrobial nanosized materials [22,23]. The above points are imperative, and addressing these limitations will enhance the applicability, safety, and scientific depth of future studies in this field.

Future Directions

This study lays a strong foundation for future research in advancing sustainable nanomaterials. One promising direction involves bandgap engineering of ZnO nanoparticles through strategic doping or forming heterojunctions with other semiconductors in order to enhance visible-light photocatalytic performance. Furthermore, evaluating the photocatalyst's effectiveness in real wastewater matrices will tend to provide insights into its behavior in these materials under complex environmental conditions. Moreover, the assessment of the regeneration and reusability of the nanoparticles is essential to determine their operational durability and economic feasibility. Finally, comprehensive toxicological assessments using model organisms, these include fish models [24], invertebrates [25,26], algae [27] and cell-based assays [28] is crucial.

Conclusion

The study by Bamisaye *et al.* underscores the adoption of eco-friendly method using *Syzygium malaccense* leaf extract to biogenically synthesize ZnO nanoparticles. The viability and application of the synthesized ZnO nanoparticles as a sustainable material for water treatment and with their antimicrobial properties was also evaluated. UV-Vis analysis showed an absorption peak at 371 nm and an optical band gap of 3.23 eV from Tauc's plot. FTIR confirmed functional groups at 574, 1033, 1188, and 1643 cm^{-1} , indicating Zn–O, Zn–O–Zn, C–O, and C=C bonds. XRD revealed a face-centered

cubic structure with a lattice parameter of 10.89 Å and an average crystallite size of 24.73 ± 2.90 nm. SEM showed slight particle clustering, while EDX detected 27.6% Zn and 61.08% O. ZnO NPs achieved 88.10% ciprofloxacin degradation (10 ppm) within 80 min using 0.4 g catalyst ($k = 0.0133 \text{ min}^{-1}$). MIC and MBC tests confirmed antimicrobial potency. As antibiotic pollution and resistance continue to pose global threats, this work contributes meaningfully to the development of multifunctional nanomaterials for next-generation environmental technologies.

Conflict of Interest Statement

The authors declare no conflict of interest.

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