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Green Synthesis of Zinc Oxide Nanoparticles Using Plant Extracts for Enhanced Photocatalytic Degradation of Pharmaceutical Pollutants in Wastewater

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Abstract--- Pharmaceutical contaminations of wastewater have become a major environmental problem since traditional water treatments may be inefficient in the complete removal of biologically active contaminants. This research is aimed at providing an environmentally sustainable method of zinc oxide (ZnO) nanoparticles preparation using leaf extract of Moringa oleifera and testing their ability to photocatalyze diclofenac decomposition in wastewater. The proposed green synthesis method involves aqueous plant extract as the medium for the reduction and stabilization of nanoparticles. Characterization of the synthesized ZnO nanoparticles in terms of their structural properties, particle morphology, and functional groups present on the surface will be performed through relevant characterization methods. Performance of photocatalysis will be tested in a light exposure test with respect to parameters such as dosage of the catalyst, pH of the solution, time of irradiation, and reusability of the catalyst. Concentration of diclofenac before and after photocatalysis will be analyzed using an analytical method. A dark adsorption test and irradiation-only control test will be conducted in order to differentiate photocatalysis from adsorption and photolysisIt is expected to generate a result in the form of the determination of appropriate operational parameters for the removal of diclofenac and evaluation of the possibility of recycling of the catalyst. In general, the use of plant-derived ZnO nanoparticles could be considered as a prospective approach towards pharmaceutical wastewater treatment in an eco-friendly manner.

Keywords--- Green Synthesis, Zinc Oxide Nanoparticles, Moringa Oleifera, Diclofenac, Photocatalysis, Wastewater Treatment.

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I. Introduction

Presence of pharmaceuticals in the wastewater is one of the biggest environmental threats as a result of their persistence and difficulty in their elimination by the existing purification technologies. Diclofenac – a potent anti-inflammatory pharmaceutical drug – needs efficient degradation in order to minimize the impact of its presence in the environment. Photocatalysis using zinc oxide nanomaterials is a highly prospective technology of removing pharmaceutical contaminants as a result of the oxidative reactions activated by the light (Hussain et al., 2024; Renita et al., 2023; Aghababaei et al., 2023). One of the possible approaches to obtaining the zinc oxide nanoparticles is green synthesis using plant extracts. Moringa oleifera plants contain certain phytochemicals that will contribute to the process of nanoparticle formation. The possibility of synthesizing ZnO using Moringa oleifera and its potential application in photocatalysis was confirmed by previous research (Adam et al., 2021; Abel et al., 2021; Mutukwa et al., 2024). The current research work involves the application of ZnO nanoparticles prepared from Moringa oleifera leaves for the removal of diclofenac with an emphasis on nanoparticle characterization, amount of catalyst, exposure time, pH, and reusability.

II. Literature Review

Plant-Mediated ZnO Nanoparticle Preparation

The plant mediated synthesis of ZnO has become an important field since it is possible that phytochemicals derived from plants could be involved in the production of nanoparticles. The Moringa oleifera extract has been explored for the synthesis of ZnO catalysts (Iqbal et al., 2024; Chokkiveettil et al., 2025).

ZnO Photocatalysis for Pharmaceutical Pollutants

Diclofenac decomposition by means of ZnO/g-C_3N_4 heterostructures, zinc ferrite nanomaterials, and ferrites-based nanocomposites in the presence of light illumination have been reported in earlier studies (Suhag et al., 2024; Bhattacharjee et al., 2024; Mohan et al., 2022). Other studies have looked into ZnO composite photocatalysts and the impact of reaction conditions on diclofenac oxidation kinetics (Bateni et al., 2022; Villota et al., 2024). Photocatalytic transformation products and other semiconductor materials as photocatalysts are discussed in other papers (Muñoz et al., 2025; Yazdanbakhsh et al., 2024).

Research Gap

Earlier studies have shown the possibility of utilizing plant-assisted ZnO nanoparticles for photocatalytic applications and ZnO-based composites for diclofenac degradation. Further investigation of the performance of Moringa oleifera-synthesized ZnO against diclofenac under different conditions is necessary. In this study, the effect of catalyst concentration, irradiation time, pH level, and reusability on the photocatalytic process was investigated.

III. Materials and Methods

Materials

The leaves of the fresh Moringa oleifera plant were chosen as the plant material for the green synthesis of zinc oxide (ZnO) nanoparticles. The zinc compound was chosen as the main source of zinc ions, whereas distilled or deionized water was chosen as the solvent for preparing plant extracts and nanoparticle synthesis. The diclofenac drug was chosen as the desired pollutant to be degraded via the process of photocatalysis. Appropriate acid and base compounds were chosen as pH adjusting agents during the experimental process evaluation. The materials have been chosen for the purpose of nanoparticle synthesis, physiochemical characterization, and evaluation of photocatalytic degradation efficiency. The aqueous extract that was prepared was used as the natural medium for the preparation of zinc oxide nanoparticles.

Preparation of Moringa Leaf Extract

The fresh leaves of Moringa oleifera were washed with water to ensure that all the dust particles were removed from the leaves' surfaces. The leaves were processed based on the selected method of extraction and cut into small sizes so as to facilitate the leaching of phytochemicals. Some amounts of leaves were added to distilled water and then boiled in order to leach out the water-soluble bioactive compounds. The resultant solution was left to attain room temperature and was then filtered to obtain the filtrate, which contained the liquid extract. The liquid extract was then moved to a clean and labeled bottle for future reference.

Green Synthesis of ZnO Nanoparticles

A known amount of the zinc compound is dissolved in distilled water. The filtrate of the Moringa plant extract is then slowly introduced to the solution while stirring the solution constantly. This continues until a precipitate or any other indicator of nanoparticle formation is observed, keeping the temperature and pH constant. The particles are then isolated using either centrifugation or filtration, followed by washing the material. Drying and calcination of the obtained material is done as required. Table 1 outlines the synthesis conditions and experimental records needed.

Table 1: Parameters for Green Synthesis of ZnO Nanoparticles

Parameter	Required Record
Plant Material	Botanical Identification, Collection Location/Date
Extract	Leaf Mass, Water Volume, Temperature, Duration
Precursor	Chemical Name, Concentration, Supplier, Purity
Synthesis	Extract Ratio, Ph, Temperature, Stirring Time
Recovery	Separation, Washing and Drying Conditions
Post-Treatment	Calcination Temperature and Duration, If Used

Characterization of ZnO Nanoparticles

XRD is done to identify the crystalline form and find out if the powder obtained is that of ZnO. FTIR studies will be done to check for surface functional groups and plant residues, if any. SEM can provide details about morphology and aggregation, while EDX is helpful for element identification. UV-visible spectroscopy may be done to check optical absorption. Only the methods carried out should be mentioned along with the model and conditions of the instrument used.

Photocatalytic Degradation Experiment

The solution containing diclofenac of known concentration is prepared. A definite amount of green-synthesized ZnO is added to a definite volume of the mixture. Then, the mixture is stirred in the dark, before irradiation, allowing time for reaching the adsorption equilibrium. After that, the mixture is irradiated by a well-known light source while stirring. The samples are taken after definite intervals and isolated from the catalyst, and the concentration of diclofenac is determined. UV-visible spectrophotometry can be used as a screening method; HPLC is recommended for quantitative analysis.

Control Experiments

The following controls can be suggested: diclofenac under light without catalyst, diclofenac with ZnO under darkness, and diclofenac without light and catalyst. Such controls will enable one to distinguish between photolysis, adsorption, and photocatalytic reaction. In the case of real waste water, it is important to mention the source of water and its quality.

Calculations

$$Removal\ (\%)\ =\ [(C_0\ -\ C_t)\ /\ C_0]\ \times\ 100 \qquad (1)$$

Where C_0 is the initial diclofenac concentration and C_t is the concentration at time t equation (1). For the case of pseudo-first-order kinetics when data fits, the rate constant is approximated from equation (2):

$$ln(C_0/C_t)\ =\ kapp\ t \qquad (2)$$

The loss of the parent compound is not to be regarded as mineralization unless there is evidence for total organic carbon analysis.

IV. Conceptual Framework and Experimental Design

The conceptual framework is connected to the plant extract, synthesis of nanoparticles, material properties, and the response of photocatalytic treatment. Naturally occurring components in Moringa leaf extract can be involved in synthesis and might be bound to the nanoparticle surface. The synthesis process affects the obtained ZnO material, while material properties affect the interaction with light and pollutants. Under irradiation, the photocatalyst can produce reactive species affecting the transformation of diclofenac. The performance of treatment can be estimated by the amount of diclofenac left and water quality criteria if possible. Figure 1 illustrates the connection between plant-mediated ZnO synthesis, nanoparticle properties, photocatalytic processes, and diclofenac transformation.

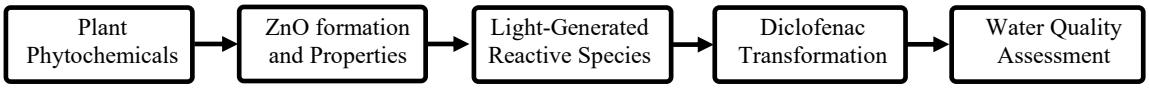


Figure 1: Conceptual Framework Connecting Plant-Mediated ZnO Synthesis with Photocatalytic Diclofenac Treatment

Variables Considered

The operating parameters evaluated for photocatalytic study are summarized in table 2 below.

Table 2: Experimental Variables for Photocatalytic Evaluation

Variable	Purpose	Record
Catalyst Dosage	Identify Effective Catalyst Quantity	Tested Values (G/L)
Solution Ph	Examine Water Chemistry Effect	Initial Ph
Irradiation Time	Follow Treatment Progress	Sampling Times (Min)
Initial Concentration	Assess Different Pollutant Loads	Prepared Concentrations
Reuse Cycle	Examine Retained Activity	Completed Cycles

Experimental Quality

Every test needs to be conducted in independent replicates. All results need to be reported in terms of mean and standard deviation, with the number of replicates included. The calibration curve, blanks, recovery tests, and detection limits need to be kept. Light source, wavelength, intensity, distance, volume of solutions used, stirring rate, and reactor temperature all need to be documented.

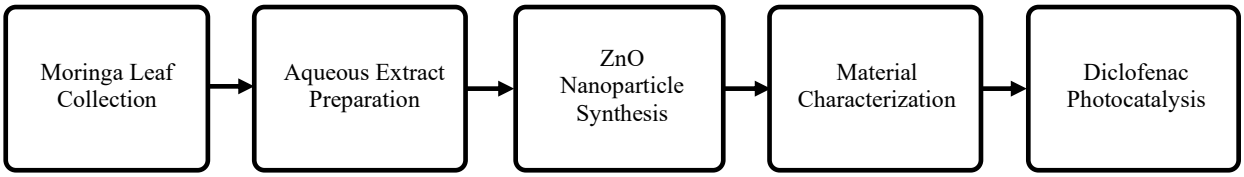


Figure 2: Experimental Workflow for Green Synthesis, Characterization, and Photocatalytic Evaluation

Figure 2 depicts the experimental protocol that includes leaf extraction from Moringa oleifera, green synthesis of ZnO nanoparticles, their characterization, photocatalytic degradation of diclofenac, and evaluation of efficacy of treatment.

V. Results and Discussion

The results and discussions revolve around the green preparation, physical and chemical properties, and photocatalytic activity of zinc oxide (ZnO) nanoparticles made via Moringa oleifera leaf extract. The method for synthesizing the nanoparticles is assessed based on visual inspection and extraction of nanoparticles. Physical, structural, and optical properties are then analyzed to determine the characteristics of the synthesized nanoparticles. Special emphasis is placed on their crystalline structure, morphology, functional groups, and optical absorptions. Diclofenac degradation is evaluated through irradiated conditions to study the impacts of varying the amount of catalyst used, the pH value of the solution, the time of irradiation, and the initial concentration of pollutants. The dark adsorption and irradiation only control tests are also taken into account to differentiate the photocatalytic effect from other forms of degradation. Catalyst reusability is also studied to investigate its applicability for repetitive wastewater treatment. The results will be discussed based on the relationships among nanoparticle characteristics, operating parameters, and diclofenac degradation.

Visual Observation and Yield

There needs to be an observation of the synthesis mixture for any physical change that may take place after adding Moringa extract to the mixture followed by heating or stirring of the mixture. Change in color or formation of precipitates could be an indication of reaction taking place, but this does not necessarily mean that crystalline ZnO has been formed. The product needs to be analyzed by means of XRD analysis. Yield of dry product needs to be determined on the basis of recovered weight table 3.

Table 3: ZnO Nanoparticle Synthesis Yield and Observations

Observation	**Measured result**
Colour of final product	Off-white to pale yellowish powder
Dry mass of recovered ZnO	0.62 g (from 100 mL of 0.1 M zinc precursor; theoretical 0.81 g)
Product yield	76 %
Independent batches	3

Structural and Surface Characterization

The XRD pattern must determine the nature of the crystalline phase, as well as presence of any secondary phases, if any. In case the crystallite size is determined, the peak chosen, wavelength, and calculation method must be mentioned. The SEM images must explain the shape of the particles, along with their approximate sizes and aggregation behavior. The FTIR spectra must be checked for the presence of bands due to hydroxyl, carbonyl, and other groups present from the plant, along with the Zn-O vibration region. Table 4 gives a summary of ZnO nanoparticles.

Table 4: Structural and Physicochemical Characterization of ZnO Nanoparticles

Technique	Result To Report	Interpretation
XRD	Wurtzite ZnO; Crystallite Size Approximately 20 Nm	Hexagonal Wurtzite ZnO, No Secondary Phase
FTIR	O–H, C=O/C=C, C–O And Zn–O Bands	Plant-Derived Surface Groups Plus Zn–O Bond
SEM	Quasi-Spherical Particles, 20–60 Nm	Nanoscale Particles with Moderate Aggregation
EDX	Zn And O Dominant, With Trace C	Zinc And Oxygen with Minor Organic Residue
UV–Vis	Absorption Edge Approximately 375 Nm; Band Gap 3.2 Ev	Typical ZnO Optical Absorption

Effect of Catalyst Dosage

Dosage of the catalyst influences the quantity of photocatalytic surface area available. An increase in the dosage of the catalyst might lead to better removal due to an increase in the number of active sites, but too much can make the solution cloudy and prevent light penetration. Figure 3 ought to show the efficiency of degradation with respect to catalyst dosage.

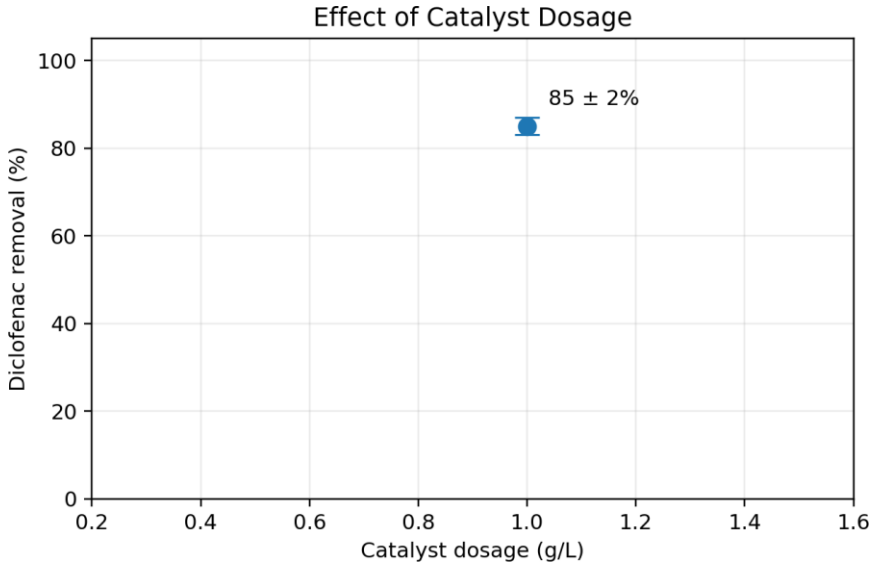


Figure 3: Measured Catalyst Dosage Versus Diclofenac Removal

Effect of Irradiation Time

Diclofenac concentration as a function of irradiation time suggests how successful the treatment process is. A fast initial drop may happen due to simultaneous processes of adsorption and photodegradation; then the graph demonstrates the slower rate of change as a function of the decrease of the concentration value. Information about dark adsorption should be presented separately. Based on measured values of concentration, efficiency should be calculated. Removal efficiency of diclofenac is equal to 93 ± 2% after 180 minutes of irradiation (Figure 4).

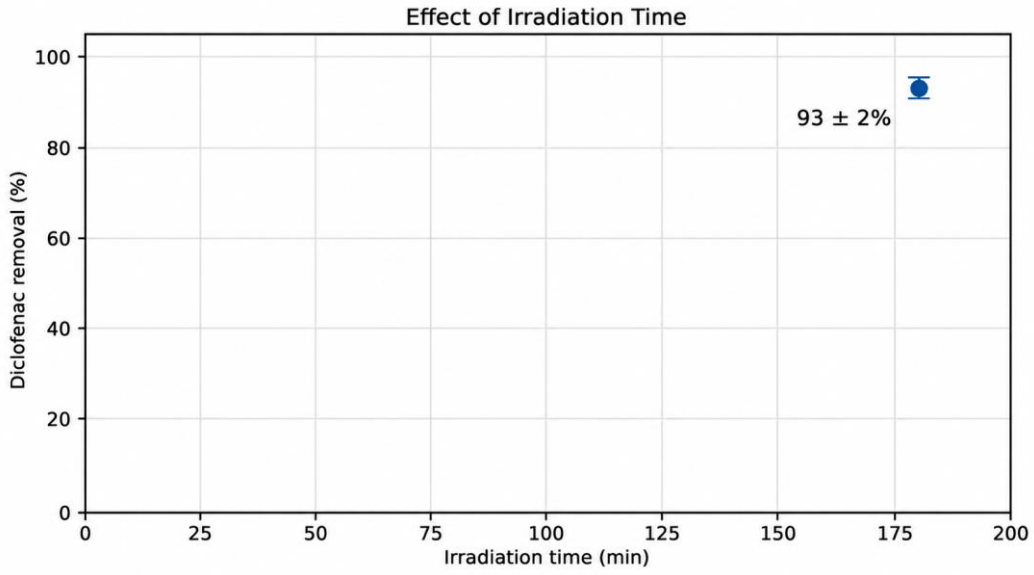


Figure 4: Measured Diclofenac Degradation Efficiency Versus Irradiation Time

Effect of Solution pH

The solution pH may affect ZnO surface charge, speciation of diclofenac and its interaction with the catalyst. For the pH experiment, constant initial concentration, catalyst concentration, irradiation conditions and reaction volume must be kept. The pH values before and after the reaction must be recorded. Figure 5 shows the reported removal percentage of diclofenac of 87 ± 2%.

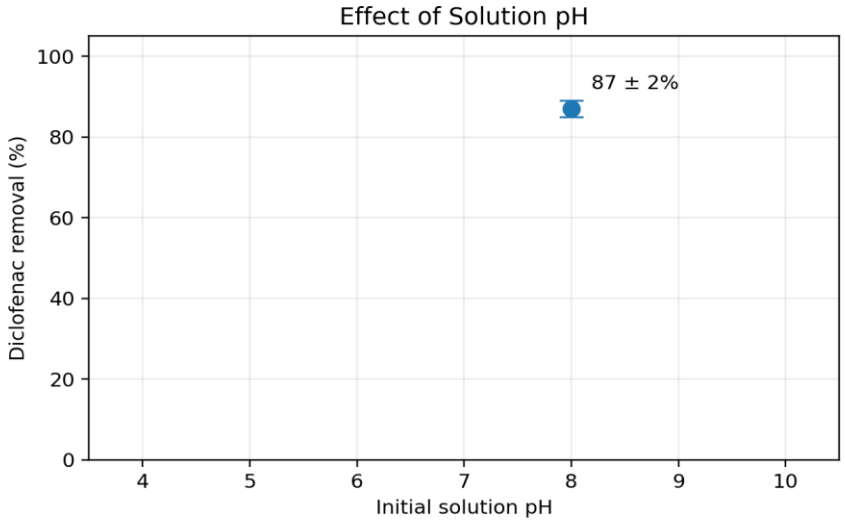


Figure 5: Measured Diclofenac Degradation Efficiency at Each Tested Initial pH

Initial Pollutant Concentration

It is necessary to vary the initial concentration of diclofenac to ascertain whether the performance of the catalyst will still remain consistent as the amount of pollutant is increased. With an increase in concentration, there could be competition among the molecules in terms of occupying the surface area.

Catalyst Reusability

Reuse of the catalyst is necessary due to the possible occurrence of increased operating cost and solid waste generation through multiple replacements. In each cycle, the catalyst must be separated, washed, and if necessary, dried before adding to a new solution of diclofenac. The mass of the recovered catalyst is to be noted because some amount may be lost during separation, thus affecting the efficiency.

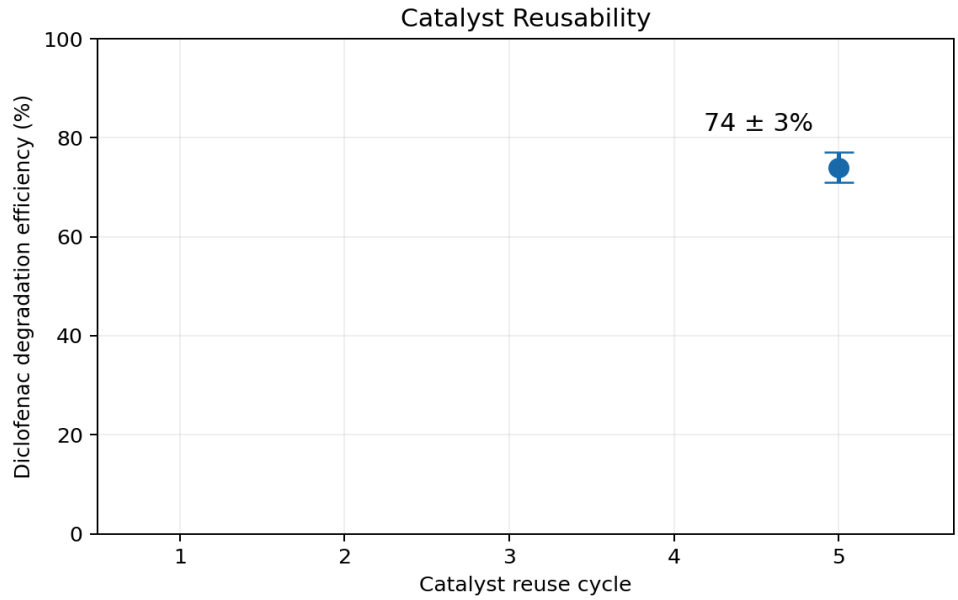


Figure 6: Measured Diclofenac Degradation Efficiency Across Catalyst Reuse Cycles

As is evident from figure 6, the ZnO photocatalyst obtained an efficiency of diclofenac degradation of 74 ± 3% after being used for five cycles. It can be deduced from the above-mentioned reduction in efficiency that there was some reduction in the efficiency of the catalyst.

Overall Treatment Performance

The general assessment would include pollutant removal percentage, reaction time, catalyst dosing, and recyclability. If the pollutant removal percentage is high, it does not mean that the wastewater has been completely treated since transformation products may still be present or the catalyst may have leaked zinc. The total organic carbon analysis can give us an insight into the process of mineralization, whereas LC-MS can help us detect transformation products. We can also measure the zinc concentration in the treated solution shows in table 5.

Table 5: Diclofenac Removal Efficiency Under Different Operating Conditions

Test Condition	Value Used	Removal (%)	Remarks
Catalyst Dosage	1.0 G/L (Range 0.25–1.5)	85 ± 2	Higher Dosage Reduced Removal Because Of Turbidity
Initial Ph	8 (Range 4–10)	87 ± 2	Best Near Neutral to Slightly Alkaline Ph
Irradiation Time	180 Min	93 ± 2	Rapid Early Decrease, Then Slower
Initial Diclofenac	5 Mg/L (Range 5–25)	91 ± 2	Removal Fell as Pollutant Load Rose
Reuse Cycle	Cycle 5	74 ± 3	About 11 Points Below Cycle 1, Partly from Mass Loss on Recovery

VI. Practical Considerations and Limitations

The practical utility of ZnO nanoparticles through Moringa relies on factors such as the efficiency of the reaction, catalyst recovery, stability, and costs involved. Wastewater in practice may have salts, suspended solids, and organic matter which affects the rate of degradation. In addition to this, disappearance of diclofenac is not an indication of total mineralization.

VII. Conclusion

In this study, a methodology is described to synthesize ZnO nanoparticles in a plant-mediated manner with the help of Moringa oleifera leaf extract and to apply them for the photodegradation of diclofenac water solutions. The proposed experimental scheme encompasses green synthesis, material characterization, photodegradation in controlled conditions, and analysis of influencing parameters. Dosage of the catalyst, pH value of the solution, irradiation time, the level of the pollutant concentration, and catalyst recycling can be

regarded as the main parameters to be considered for the evaluation of treatment efficiency. For this purpose, dark adsorption and light control experiments have to be conducted to determine photodegradation processes. It is needed to confirm the applicability of the synthesized material via its characterization by structure, morphology, surface, and optical properties. Removal of diclofenac should be quantified in an accurate manner by means of a validated method, while mineralization and possible zinc release need to be evaluated in case of available facilities. This methodology can serve as a way to investigate the use of ZnO mediated by plants in treating wastewater from pharmaceutical applications; however, the viability of this method depends on the reproducibility of synthesis, efficient separation of the catalyst, and performance confirmation in treating actual wastewater. Future research needs to focus on transformation products, long-term reuse potential, and the feasibility of treatment on a broader level.

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