# Green Synthesis of *Acacia nilotica*-Mediated ZnO Nanoparticles for the Photocatalytic Degradation of Methylene Blue Dye

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**Abstract:** In recent years, plant extract-mediated green synthesis of semiconductor nanoparticles has emerged as a sustainable, low-cost, and eco-friendly technique for wastewater treatment applications. The present study aimed to synthesize zinc oxide (ZnO) nanoparticles using *Acacia nilotica* leaf extract and evaluate their photocatalytic efficiency for the degradation of methylene blue (MB) dye under visible light irradiation. The findings suggest that *Acacia nilotica*-mediated ZnO nanoparticles are an efficient, environmentally friendly, and cost-effective photocatalyst with considerable potential for the treatment of dye-contaminated wastewater.

**Keywords:** *Acacia nilotica*; Green synthesis; ZnO NPs; Photocatalytic degradation; Methylene blue.

## 1. Introduction: -

The textile industry is one of the most important industries worldwide, as its products fulfil essential human needs while also enhancing comfort, lifestyle, and luxury. It produces a wide variety of products, including clothing, home furnishings, automotive textiles, and several other textile-based materials. Despite its significant economic contribution, textile processing is recognized as one of the major sources of environmental pollution, affecting water, air, and soil quality [1]. Among the different pollutants released from textile industries, textile dyes have emerged as a serious environmental concern across the globe. These dyes are commonly discharged into rivers, lakes, and other water bodies, which are essential components of aquatic ecosystems, thereby posing risks to both the environment and human health [2]. The presence of textile dyes in water not only reduces its aesthetic appeal but also increases BOD and COD, limits light penetration, inhibits photosynthesis, restricts plant growth, and enters the food chain through bioaccumulation. Furthermore, many dye compounds are toxic and may exhibit mutagenic and carcinogenic effects, making them harmful to living organisms [3].

Dyes are colouring substances that impart colour to a material under suitable conditions depending on the nature of the substrate. They produce colour either by staining the material or by being absorbed after dissolving in a suitable medium [4]. Based on their origin, dyes are broadly classified into two categories: natural dyes and synthetic dyes [5]. With the continuous development of the textile industry, the number and variety of dyes have increased considerably, making their classification increasingly important. Depending on their chemical structure, textile dyes are grouped into classes such as azo, anthraquinone, phthalocyanine, sulphur, indigo, nitro, and nitroso dyes. They can also be classified according to their industrial application methods into reactive, direct, acid, basic, vat, disperse, and other dye categories [6].

The removal and degradation of dye pollutants from industrial wastewater remain challenging because many synthetic dyes possess stable and complex molecular structures that resist natural degradation. Owing to their persistence in the environment and their potential genotoxic effects, a wide range of physical, chemical, and biological treatment methods have been explored for dye removal from wastewater [7]. Physical treatment methods include adsorption, membrane separation, and ion exchange, while chemical approaches involve oxidation processes such as Fenton oxidation, ozonation, and persulfate oxidation. Biological treatment methods include aerobic and anaerobic processes, as well as bacterial, algal, fungal, and enzymatic degradation. Among these, biological treatment is widely preferred because it is simple, economical, environmentally friendly, and effective in reducing chemical oxygen demand (COD). However, it is mainly suitable for biodegradable organic pollutants and is generally ineffective for non-biodegradable and refractory dye compounds. The highly stable molecular structures of many synthetic dyes make them resistant to microbial degradation, limiting the efficiency of biological treatment alone [8].

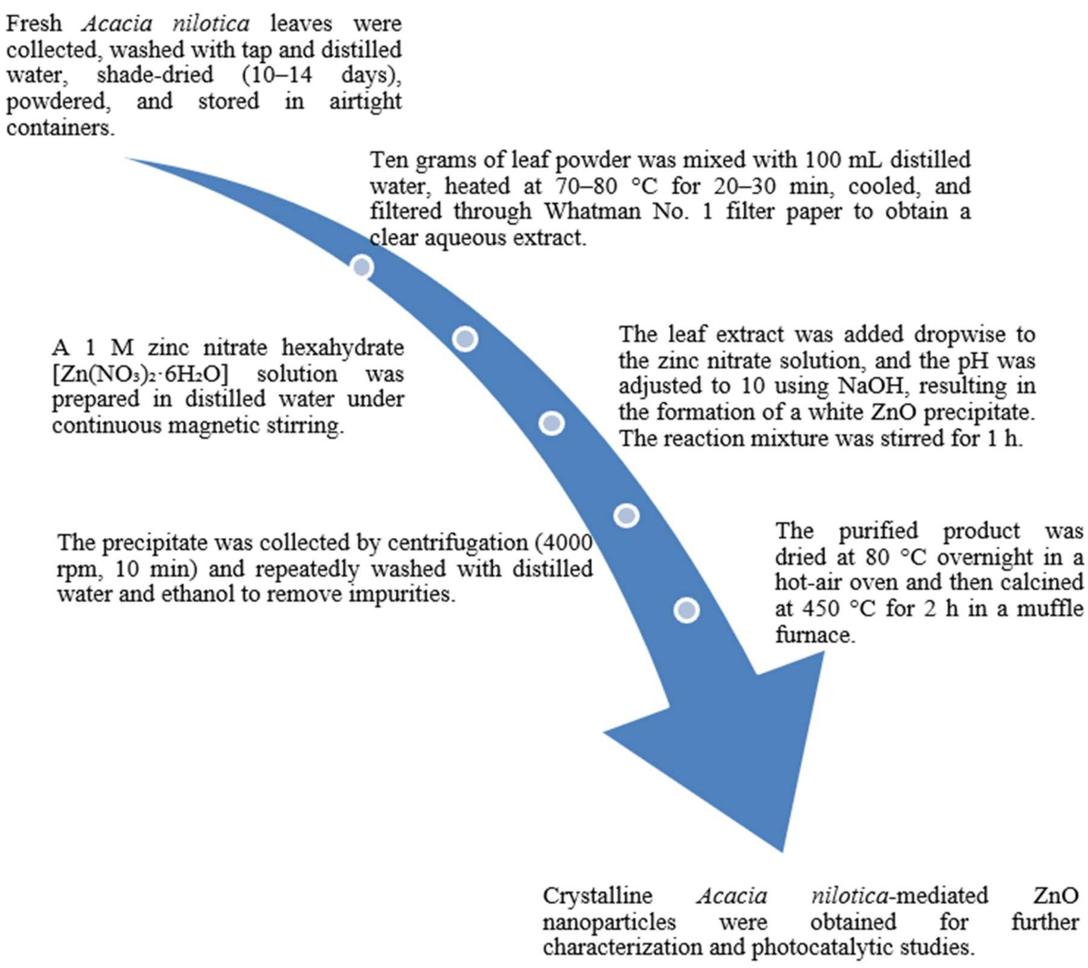
In recent years, photocatalytic degradation using nanoparticles has emerged as an effective and environmentally friendly approach for the treatment of dye-contaminated wastewater. In this process, organic dye molecules are degraded under ultraviolet or visible light irradiation in the presence of a suitable photocatalyst. Compared with conventional treatment methods, photocatalysis is cost-effective, highly efficient, and does not generate harmful polycyclic by-products during the degradation process [9]. In view of these advantages, the present study aims to green synthesize *Acacia nilotica*-mediated ZnO nanoparticles and evaluate their photocatalytic efficiency for the degradation of methylene blue dye under visible light irradiation.

## 2. Research Methodology: -

### 2.1. Preparation of ZnO NPs:

Figure 1 illustrates the sequential steps involved in the green synthesis of *Acacia nilotica*-mediated ZnO nanoparticles. The process includes the preparation of the leaf extract, synthesis of ZnO nanoparticles using zinc nitrate as the precursor, purification, drying, calcination, and the final production of crystalline ZnO nanoparticles for characterization and photocatalytic degradation studies.

**Fig. 1: Schematic illustration of the green synthesis of *Acacia nilotica*-mediated ZnO nanoparticles**




### 2.2. Assessment of Photocatalytic Activity:

The photocatalytic performance of the green-synthesized *Acacia nilotica*-mediated

ZnO nanoparticles was evaluated using MB dye under visible light irradiation. A known amount of ZnO nanoparticles was dispersed in 100 mL of MB solution with an initial concentration of 10 mg/L and continuously stirred using a magnetic stirrer to ensure uniform suspension of the photocatalyst. At regular time intervals, aliquots were withdrawn, and the photocatalyst was separated by centrifugation before measuring the absorbance of the clear solution using a UV–Visible spectrophotometer at 665 nm, corresponding to the maximum absorption wavelength of methylene blue. The degradation efficiency was calculated using:

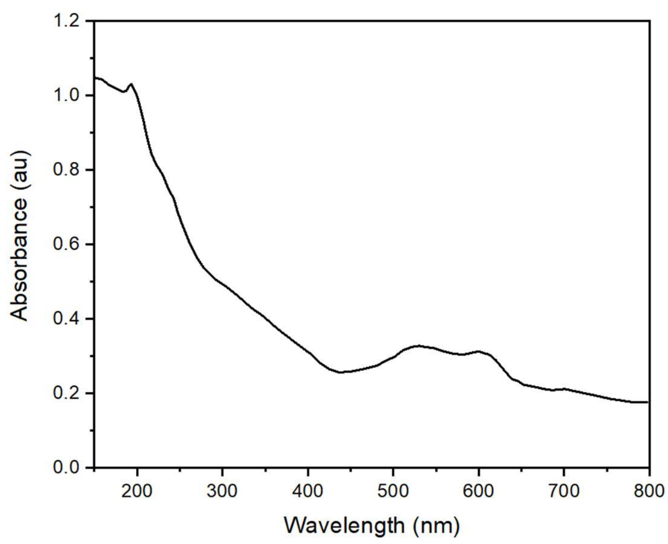
$$\text{Degradation } \% = \frac{C_o - C_t}{C_o} \times 100$$

where $C_0$(mg/L) is the initial conc. of MB dye and $C_t$(mg/L) is the conc. of the dye at irradiation time $t$.

## 3. Result and Discussion: -

The optical band gap of the green-synthesized *Acacia nilotica*-mediated ZnO nanoparticles was found to be 2.97 eV. This value is slightly lower than the band gap of bulk ZnO (≈3.37 eV), indicating that the green synthesis process and the phytochemicals present in the *Acacia nilotica* leaf extract may have introduced surface defects, oxygen vacancies, or impurity levels within the ZnO lattice. These defect states reduce the band gap.

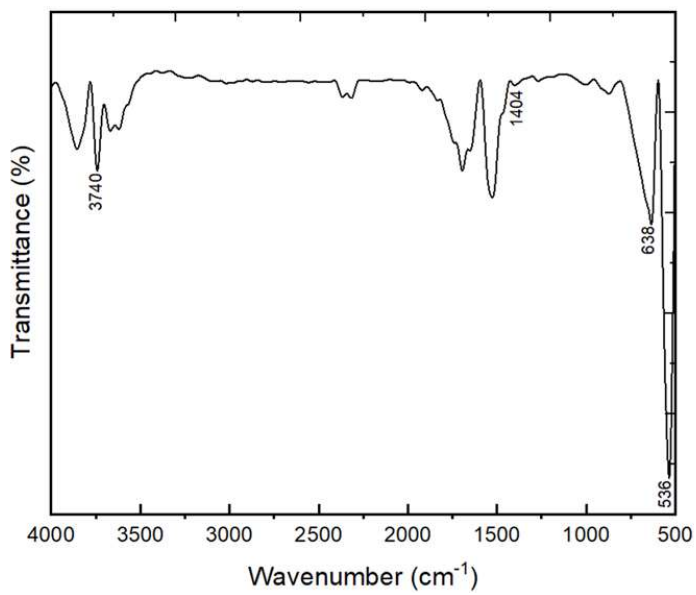
**Fig. 2: UV–Visible absorption spectrum of green-synthesized *Acacia nilotica*-mediated ZnO nanoparticles**




The narrowed band gap contributes to the improved photocatalytic degradation of methylene blue by promoting the formation of reactive oxygen species and reducing the recombination rate of photogenerated charge carriers [10-13].

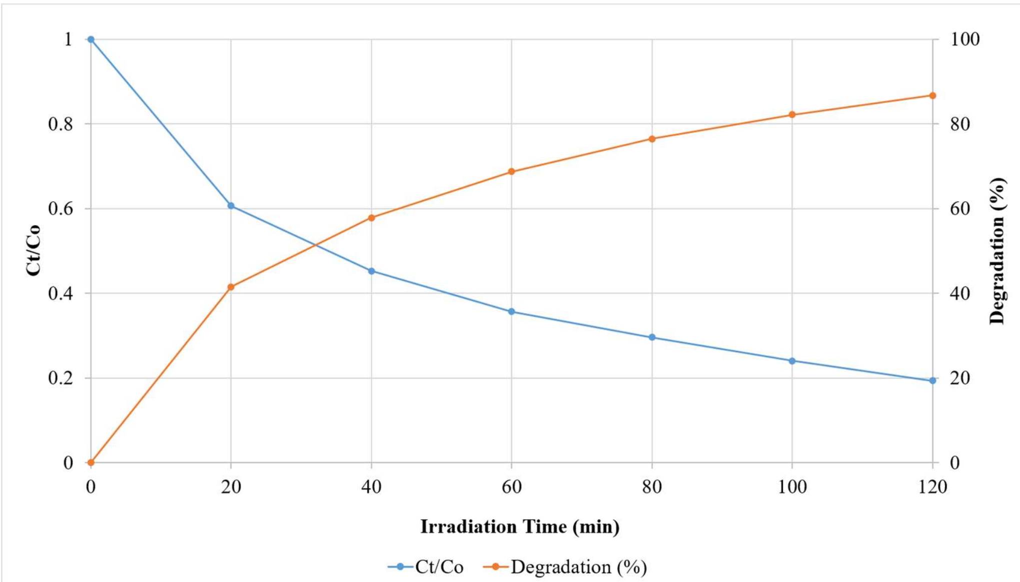
The FTIR spectrum of the green-synthesized *Acacia nilotica*-mediated ZnO NPs confirmed the successful formation of ZnO. The FTIR spectrum exhibited a prominent band at 3740 $cm^{-1}$, which is attributed to the stretching vibration of hydroxyl (–OH) groups originating from surface-bound water molecules. A distinct peak at 1404 $cm^{-1}$ was assigned to the stretching of aromatic carbon–carbon (C=C) bonds, suggesting the presence of phytochemical constituents from *Acacia nilotica* that participated in the reduction of zinc ions and provided stability to the synthesized nanoparticles during the green synthesis process [14,15]. Strong absorption bands observed at 638 $cm^{-1}$ and 536 $cm^{-1}$ correspond to the characteristic Zn–O vibrational modes, confirming the successful formation of ZnO nanoparticles with a crystalline structure. The coexistence of Zn–O vibrations and plant-derived functional groups indicate that the biomolecules present in the *Acacia nilotica* leaf extract played a dual role in facilitating nanoparticle formation and preventing their agglomeration, thereby producing stable ZnO NPs.

**Fig. 3: FTIR spectrum of green-synthesized *Acacia nilotica*-mediated ZnO NPs**




The photocatalytic degradation of MB dye using *Acacia nilotica*-mediated ZnO nanoparticles increased steadily with irradiation time, demonstrating the excellent photocatalytic activity of the green-synthesized nanoparticles. No degradation was observed at 0 min, while 41.48% degradation was achieved within the first 20 min, indicating rapid dye decomposition due to the generation of ROS under light irradiation. The degradation efficiency further increased to 57.82%, 68.74%, 76.42%, and 82.16% at 40, 60, 80, and 100 min, respectively. A maximum degradation efficiency of 86.65% was attained after 120 min, confirming the effective degradation of MB dye. The gradual increase in degradation efficiency with irradiation time highlights the high catalytic efficiency and potential of *Acacia nilotica*-mediated ZnO nanoparticles as an eco-friendly photocatalyst for wastewater treatment [16-21].

**Fig. 4: Effect of irradiation time on the photocatalytic degradation efficiency of MB over *Acacia nilotica*-mediated ZnO NPs**




## 4. Conclusion: -

The present study successfully demonstrated the green synthesis of ZnO NPs using *Acacia nilotica* leaf extract through a simple, eco-friendly, and cost-effective approach. UV–Visible analysis revealed an optical band gap of 2.97 eV, indicating enhanced visible-light absorption compared with bulk ZnO, while FTIR analysis confirmed the successful formation of crystalline ZnO NPs. The synthesized ZnO nanoparticles exhibited remarkable photocatalytic activity, achieving a maximum degradation efficiency of 86.65% within 120 min. The gradual increase in degradation efficiency with irradiation time demonstrated the effective generation of ROS and efficient degradation of dye molecules. Overall, the results confirm that *Acacia nilotica*-mediated ZnO nanoparticles possess excellent photocatalytic properties and represent a promising sustainable material for the treatment of dye-containing wastewater. The green synthesis approach also offers significant environmental and economic advantages, making these nanoparticles suitable candidates for future applications in wastewater remediation and environmental protection.

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