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# Induced Zinc Oxide Nanoparticles and Photocatalytic Degradation

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**ABSTRACT:** The growing threat of water pollution due to industrial discharge, especially from dyes like methylene blue (MB), necessitates the development of advanced remediation techniques. This study investigates the use of zinc oxide (ZnO) nanoparticles as a photocatalyst for the efficient degradation of MB under UV light irradiation. ZnO, with its wide band gap, high photochemical stability, and strong oxidative properties, demonstrates significant potential in environmental remediation. The photocatalytic efficiency is enhanced by leveraging the unique properties of nanoscale ZnO, including increased surface area-to-volume ratio and enhanced light absorption. Key experimental parameters, such as ZnO nanoparticle concentration, light intensity, and dye concentration, are explored to optimize the degradation process. Characterization techniques like X-ray diffraction (XRD), scanning electron microscopy (SEM), and UV-visible spectroscopy are employed to analyze the structural, morphological, and optical properties of the synthesized ZnO nanoparticles. The findings confirm the effectiveness of ZnO nanoparticles in degrading methylene blue, providing insights into their broader applicability in wastewater treatment. This work highlights the potential of nanotechnology-based green solutions for addressing environmental challenges.

**KEYWORDS:** Photocatalysis, Zinc Oxide Nanoparticles(ZnO), Methylene Blue Degradation, Water Pollution, Nanotechnology, Environmental Remediation, UV Light Irradiation, Wastewater Treatment

## I. INTRODUCTION

The rapid industrialization and urbanization in recent decades have led to the discharge of a large number of pollutants, including dyes, into water bodies. These dyes, commonly used in industries such as textiles, paper, and plastics, contribute significantly to water pollution and pose serious environmental and health hazards. Among these pollutants, methylene blue (MB) is a widely used organic dye, notorious for its toxicity and persistence in water ecosystems. Traditional wastewater treatment methods, such as physical filtration and chemical precipitation, often fail to completely remove dyes like MB, necessitating the development of advanced methods to tackle this issue.

Photocatalysis, a process driven by light energy to accelerate a chemical reaction, has emerged as a promising solution for environmental remediation, particularly in the degradation of organic pollutants like dyes. Zinc oxide (ZnO), a well-known semiconductor material, has gained significant attention due to its wide band gap (3.37 eV), strong oxidation capability, and high photochemical stability, making it an effective photocatalyst. Under light irradiation, ZnO generates electron-hole pairs, which can participate in redox reactions to degrade pollutants. The energy gap of ZnO allows it to utilize UV light for initiating these reactions, leading to the mineralization of organic compounds into less harmful substances such as carbon dioxide and water.

Nanotechnology has further enhanced the capabilities of ZnO as a photocatalyst. When reduced to the nanoscale, ZnO nanoparticles exhibit unique properties such as a high surface area-to-volume ratio, enhanced surface reactivity, and improved light absorption, which contribute to increased photocatalytic activity. These nanoscale ZnO particles can degrade a wide range of organic pollutants, including dyes like methylene blue, with greater efficiency compared to their bulk counterparts.

In this project, we focus on the synthesis and characterization of ZnO nanoparticles and their application in the photocatalytic degradation of methylene blue under UV light irradiation. The study explores the role of

ZnO nanoparticle concentration, light intensity, and dye concentration in influencing the efficiency of the photocatalytic process. Various characterization techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM),

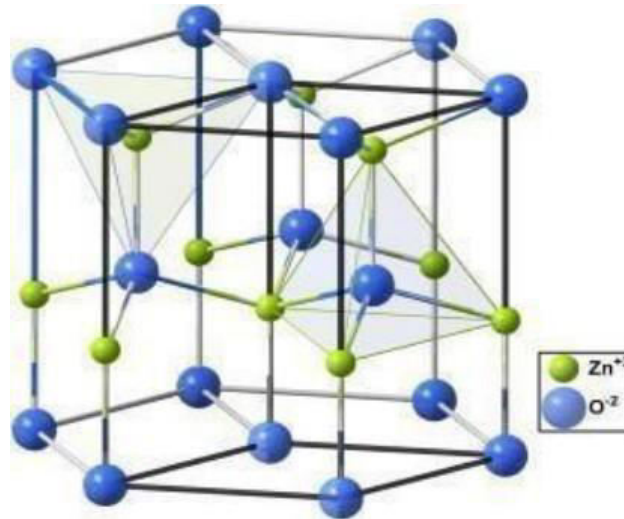


Figure 1: Structure of ZnO Nanoparticles.

and UV-visible spectroscopy, are employed to evaluate the structural, morphological, and optical properties of the synthesized ZnO nanoparticles.

The project aims to demonstrate the effectiveness of ZnO nanoparticles as a photocatalyst for degrading methylene blue, providing insights into their potential applications in real-world water treatment systems. By optimizing the degradation conditions, this study contributes to the growing research on using semiconductor nanoparticles for environmental remediation, particularly for the treatment of dyepolluted wastewater. This work is also intended to highlight the importance of green and sustainable technologies in addressing global environmental challenges.

#### Structure of ZnO Nanoparticles

Zinc oxide (ZnO) is a wide-bandgap semiconductor with a wurtzite crystal structure, which is the most thermodynamically stable form at ambient conditions. The wurtzite structure is a hexagonal arrangement, characterized by a combination of tetrahedral coordination where each zinc ion ( $Zn^{2+}$ ) is surrounded by four oxygen ions ( $O^{2-}$ ) and vice versa. This tetrahedral bonding in ZnO creates a non-central symmetric crystal, leading to piezoelectric properties, which will be discussed later. ZnO nanoparticles exhibit a large surface-to-volume ratio due to their nanoscale dimensions, which enhances their reactivity and interaction with external stimuli, such as light and pollutants. The size and morphology of ZnO nanoparticles can vary depending on the synthesis method used, ranging from spherical to rod-like or needle-like structures. The crystalline structure of ZnO nanoparticles can be confirmed using techniques such as X-ray diffraction (XRD), where typical peaks at specific  $2\theta$  angles indicate the wurtzite structure. The structure of ZnO nanoparticles plays a key role in their photocatalytic activity, as the exposed crystal facets, surface defects, and oxygen vacancies contribute to their reactivity. These factors enhance the ability of ZnO nanoparticles to generate electron-hole pairs under UV irradiation, which is essential for the photocatalytic degradation of organic pollutants like methylene blue.

## II. REVIEW OF LITERATURE

The photocatalytic properties of ZnO nanoparticles (NPs) have been extensively studied in recent years, particularly in the context of environmental remediation. This section provides a detailed review of the literature related to the synthesis of induced ZnO nanoparticles, their photocatalytic mechanisms, and various factors influencing their performance.

**Fundamental Studies on ZnO Nanoparticles as Photocatalysts**

- Zinc oxide (ZnO) has been recognized as a promising photocatalyst due to its wide bandgap ( 3.37 eV) and high exciton binding energy ( 60 meV), which contribute to its strong oxidative capacity and chemical stability. The early studies by Mishra and Sharma (2012) highlighted the potential of ZnO as an alternative to TiO for photocatalytic degradation of organic pollutants in water. The study emphasized ZnO's superior photocatalytic performance in terms of its ability to generate electron-hole pairs under UV light, leading to the production of reactive oxygen species (ROS) like hydroxyl ( $\bullet\text{OH}$ ) and superoxide radicals ( $\text{O}\bullet$ ), which are responsible for breaking down organic molecules.
- However, one of the key limitations identified in these early studies was the limited absorption of ZnO under visible light due to its wide band gap. This spurred extensive research into doping and modifying ZnO to enhance its photocatalytic performance under a broader spectrum of light

**Morphology and Size-Dependent Photocatalytic Properties**

- Jain et al. (2015) provided a comprehensive review of how the morphology and size of ZnO nanoparticles influence their photocatalytic activity. Their study highlighted that nanoscale ZnO particles with different morphologies—such as rods, spheres, and nanoflowers— exhibited varying levels of photocatalytic efficiency. The authors found that rod-like and flower-like ZnO nanoparticles exhibited better light absorption and photocatalytic performance than spherical nanoparticles, which they attributed to increased surface area and the exposure of more active sites.
- Similarly, Khan et al. (2018) demonstrated that the size of ZnO nanoparticles plays a critical role in photocatalytic activity. Nanoparticles with smaller sizes ( $\leq 20$  nm) showed significantly enhanced photocatalytic degradation of organic pollutants compared to larger particles. This improvement was due to the higher surface-to-volume ratio of smaller particles, which provides more active sites for the degradation reactions.

**Photocatalytic Mechanism of ZnO Nanoparticles**

- The photocatalytic mechanism of ZnO nanoparticles has been well documented in literature, with key studies focusing on the generation of reactive oxygen species (ROS). Kamat (2008) provided one of the seminal reviews of semiconductor photocatalysis, detailing how ZnO and similar semiconductors generate electron-hole pairs upon excitation by light. The review outlined the steps of photocatalytic degradation, starting with the absorption of photons with energy greater than the bandgap, leading to the formation of electron-hole pairs. These pairs migrate to the surface of ZnO nanoparticles, where they participate in oxidation-reduction reactions, producing hydroxyl and superoxide radicals responsible for pollutant degradation.
- Recent studies by Chen et al. (2020) expanded on this mechanism, showing that doping ZnO can further improve the efficiency of ROS generation by enhancing charge separation and reducing recombination. Their experiments demonstrated that dopants such as  $\text{Fe}^*$  and  $\text{Ag}^+$  introduced energy levels within the ZnO bandgap, which act as traps for electrons, prolonging their lifetime and increasing the likelihood of interaction with oxygen to produce superoxide radicals.

**Factors Influencing Photocatalytic Efficiency**

- Several studies have investigated the factors that influence the photocatalytic activity of ZnO nanoparticles, including light intensity, pH of the reaction medium, and catalyst loading.
- Nakata and Fujishima (2012) studied the effect of light intensity on the photocatalytic degradation of organic dyes. They found that increasing light intensity increased the rate of photocatalytic degradation due to the generation of more electron-hole pairs. However, they also noted that beyond a certain threshold, further increases in light intensity led to reduced efficiency due to saturation effects and increased recombination of electron-hole pairs.
- Rahman et al. (2014) investigated the impact of pH on the photocatalytic degradation of phenol using ZnO nanoparticles. They found that ZnO exhibited the highest photocatalytic activity in alkaline conditions (pH 9-10), where the surface of ZnO was negatively charged, enhancing the interaction with positively charged pollutants. In contrast, acidic conditions (pH  $\leq 4$ ) resulted in lower photocatalytic efficiency due to the protonation of the surface hydroxyl groups, which hindered pollutant adsorption.
- Zhu et al. (2016) explored the effect of catalyst loading on photocatalytic efficiency, noting that increased ZnO concentration initially improved degradation rates due to more available active sites. However, beyond

a certain loading (1 g/L), further increases led to diminished returns, as excess ZnO particles caused light scattering, reducing the effective irradiation of the catalyst surface.

### III. MATERIALS AND METHODS

In this method, zinc acetate dihydrate ( $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$ ) is used as the precursor for zinc ions, and sodium hydroxide (NaOH) acts as a precipitating agent to form zinc oxide (ZnO) nanoparticles. The synthesis follows a chemical precipitation process, with the reaction taking place in an aqueous solution.

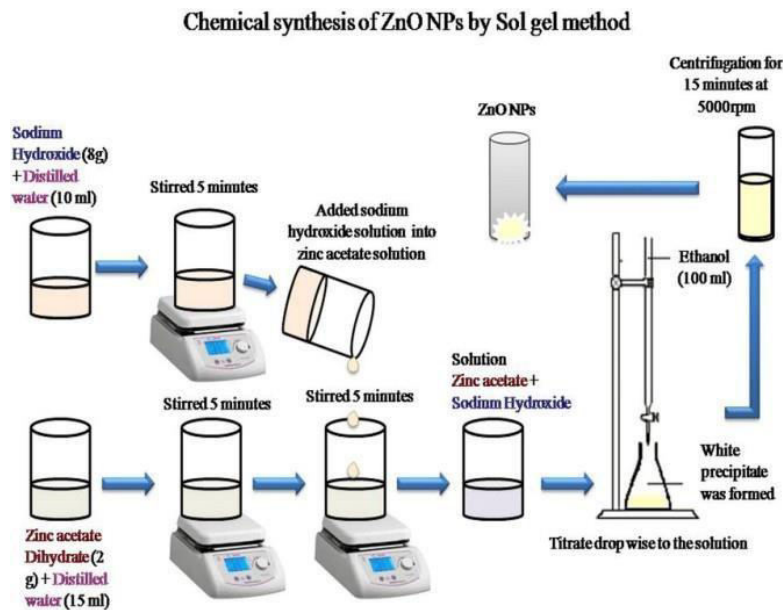


Figure 2: Chemical synthesis of ZnO NPs by Sol gel process

Materials Required:

- Zinc Acetate Dihydrate ( $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$ ) – Zinc precursor for the reaction.
- Sodium Hydroxide (NaOH) – Precipitating agent to form ZnO.
- Distilled Water – Solvent for solution preparation.
- Ethanol ( $\text{CH}_3\text{OH}$ ) – Used for washing and purifying ZnO nanoparticles.
- Magnetic Stirrer with Hotplate – For stirring and controlling the reaction temperature.
- Centrifuge – For separating and collecting ZnO nanoparticles.
- Beakers, Glassware, and Measuring Cylinders – For handling and preparing solutions.
- Oven – For drying the synthesized nanoparticles.
- Thermometer – To monitor temperature during the reaction.

Production of ZnO nanoparticles:

- Preparation of Zinc Acetate Solution
  - a) Weigh 2 g of zinc acetate dihydrate ( $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$ ) and dissolve it in 15 mL of distilled water in a beaker.
  - b) Place the beaker on a magnetic stirrer and stir the solution continuously until the zinc acetate is completely dissolved. The solution should appear clear and homogeneous.
- Preparation of Sodium Hydroxide Solution
  - a) In a separate beaker, prepare a 0.4 M 8g sodium hydroxide (NaOH) solution by dissolving the required amount of NaOH in 10 mL of distilled water. Stir the solution thoroughly to ensure the complete dissolution of NaOH.

- b) Monitor the temperature of the NaOH solution to ensure that it remains at room temperature (25-30°C) before adding it to the zinc acetate solution.
- c) Mix both the Zinc Acetate solution and Sodium Hydroxide solution and stir it for 5 mins using Under continuous stirring, slowly add the Ethanol solution dropwise to the zinc acetate solution. magnetic stirrer.

- **Precipitation of ZnO Nanoparticles**

- a. This step should be done slowly to avoid sudden precipitation and ensure uniform mixing. During the addition of Ethanol, the pH of the solution will increase, and a white precipitate of zinc hydroxide ( $Zn(OH)_2$ ) will begin to form. Continue stirring the mixture for 30 minutes after the addition is complete.

The chemical reaction occurring during the heat treatment is:  $Zn(OH)_2 \rightarrow ZnO + H_2O$

As the reaction progresses, the white precipitate will convert into ZnO nanoparticles, which remain suspended in the solution.

- **Washing and Purification of ZnO Nanoparticles**

- a) After completing the heat treatment, allow the solution to cool to room temperature.
- b) Centrifuge the reaction mixture at 3000-4000 rpm for 10 minutes to collect the ZnO nanoparticles from the solution.
- c) Decant the supernatant and wash the ZnO nanoparticles with distilled water to remove any unreacted chemicals and by-products.
- d) To further purify the ZnO nanoparticles, wash them with ethanol to eliminate any organic impurities. Centrifuge the nanoparticles again to collect the purified ZnO.

- **Drying the ZnO Nanoparticles**

- a) After washing, transfer the collected ZnO nanoparticles to a clean petri dish or container.
- b) Place the nanoparticles in an oven set at 60-80°C and allow them to dry for several hours.
- c) Once dried, the ZnO nanoparticles can be gently ground to obtain a fine powder. Store the dried nanoparticles in a sealed container for further characterization and use.

- **Characterization of Induced ZnO Nanoparticles** Characterizing induced ZnO nanoparticles is critical for understanding their structural, optical, and chemical properties, which directly affect their photocatalytic performance. A combination of techniques is used to provide detailed insights into the morphology, crystallinity, particle size, elemental composition, and optical properties of ZnO nanoparticles. This section describes the various characterization methods employed to evaluate the properties of ZnO nanoparticles, particularly after doping or surface modification.

i. **X-ray Diffraction (XRD):**

X-ray diffraction (XRD) is a widely used technique to analyze the crystalline structure of ZnO nanoparticles. It helps in identifying the phase purity, crystallite size, and lattice parameters of the synthesized nanoparticles. The XRD pattern of ZnO nanoparticles typically shows characteristic peaks corresponding to the hexagonal wurtzite structure.

- **Crystalline Structure:** ZnO nanoparticles exhibit a hexagonal wurtzite crystal structure, which is confirmed by the presence of strong diffraction peaks at angles  $2\theta = 31.7^\circ, 34.4^\circ, 36.2^\circ, 47.5^\circ, 56.6^\circ, 62.8^\circ,$  and  $68.0^\circ$ , corresponding to the planes (100), (002), (101), (102), (110), (103), and (112), respectively. Induced ZnO nanoparticles often show slightly broader peaks than pure ZnO, indicating a reduction in crystallite size, especially after doping. The typical crystallite size for ZnO nanoparticles ranges from 20 to 50 nm, depending on synthesis conditions and dopants used.

ii. **Scanning Electron Microscopy (SEM) :**

Scanning Electron Microscopy (SEM) provides high-resolution images of the surface morphology and particle size of ZnO nanoparticles. SEM allows for a detailed observation of the shape, size, and distribution of particles.

- **Surface Morphology:** ZnO nanoparticles typically exhibit various morphologies such as spherical, rod-like, or flower-like structures. Induced ZnO nanoparticles often show slight variations in morphology due to the

presence of dopants or surface modifications. For instance, metal-doped ZnO nanoparticles may exhibit rougher or more irregular surfaces.

- Particle Size and Shape: SEM analysis typically shows that ZnO nanoparticles have sizes ranging from 20 to 50 nm. Metal or non-metal doping can influence particle growth, sometimes resulting in elongated shapes or agglomeration. The SEM images confirm the homogeneous distribution of nanoparticles and provide insights into their surface roughness, which is important for photocatalytic activity.

iii. Transmission Electron Microscopy (TEM) :

Transmission Electron Microscopy (TEM) is used to obtain more precise information about the internal structure, particle size, and crystallinity of ZnO nanoparticles. TEM provides higher resolution than SEM, allowing for the visualization of individual nanoparticles and their internal lattice structures.

- Nanoparticle Size: TEM images confirm the particle size distribution, revealing the nanoparticles as individual crystallites or agglomerates. The particles are typically found in the range of 10 to 50 nm.
- Lattice Structure: High-resolution TEM (HRTEM) can visualize the lattice fringes of the nanoparticles, providing direct evidence of crystallinity. The spacing between the fringes corresponds to the interplanar distance (d-spacing) of specific crystallographic planes, which can be used to confirm the ZnO crystal structure.
- Dopant Distribution: TEM with energy-dispersive X-ray spectroscopy (EDX) can be used to map the elemental distribution in doped ZnO nanoparticles, confirming the presence and uniform dispersion of dopant ions.

iv. UV-Visible Spectroscopy (UV-Vis) :

UV-Visible spectroscopy is a key technique for assessing the optical properties of ZnO nanoparticles, particularly their light absorption characteristics and band gap energy. Absorption Spectra: Pure ZnO nanoparticles typically

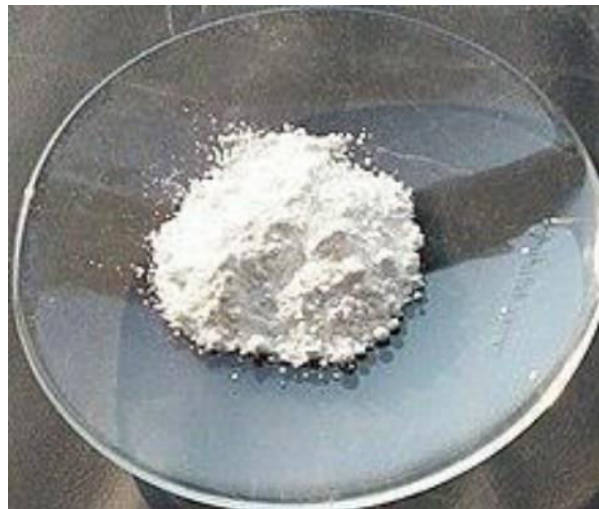


Figure 3: ZnO Nanoparticles

show a strong absorption peak in the UV region around 350-380 nm, corresponding to the intrinsic bandgap of ZnO (3.37 eV). After doping, a shift in the absorption edge toward longer wavelengths (red shift) is observed, indicating a reduction in the band gap energy and enhanced visible light absorption.

**Photocatalytic degradation of methylene blue (MB) :**

Photocatalytic degradation using ZnO nanoparticles is a well-established method for breaking down organic pollutants in water or air. Here's a general procedure to conduct a photocatalytic degradation experiment using ZnO nanoparticles: Materials Required:

- ZnO nanoparticles (acting as the photocatalyst)

- Pollutant/organic dye (like methylene blue)
- UV light source (e.g., UV lamp or solar simulator)

- Water solvent (to prepare the pollutant solution)
- Glassware (beakers, conical flasks, etc.)
- Stirring setup (magnetic stirrer)
- pH meter (optional, to monitor pH)
- UV-Vis spectrophotometer (to monitor degradation)

**Procedure:**

- Preparation of Pollutant Solution: Dissolve the organic pollutant (e.g., methylene blue) in distilled water to prepare a standard solution with a known concentration (e.g., 10-50 mg/L).
- Addition of ZnO Nanoparticles: Add a known concentration of ZnO nanoparticles (typically between 0.1 to 1 g/L) to the pollutant solution. The amount can be varied depending on the desired degradation efficiency. Stir the mixture well using a magnetic stirrer to ensure proper dispersion of the nanoparticles.
- pH Adjustment (Optional): If necessary, adjust the pH of the solution using dilute acid (e.g., HCl) or base (e.g., NaOH), since pH can influence photocatalytic activity. Most photocatalytic reactions are carried out in slightly acidic to neutral conditions (pH 5-7).
- Exposure to UV Light: Place the reaction mixture under a UV light source. Typically, UV lamps with wavelengths around 365 nm are used, but ZnO can also be activated by solar light. Maintain constant stirring throughout the exposure to ensure uniform dispersion of nanoparticles and pollutants.
- Sampling: At regular time intervals (e.g., every 15-30 minutes), take small aliquots of the solution to monitor the progress of the degradation process.
- Analysis: Analyse the aliquots using a UV-Vis spectrophotometer to measure the absorbance of the pollutant at its characteristic wavelength (e.g., 664 nm for methylene blue). The decrease in absorbance over time indicates the degradation of the pollutant.

**IV. RESULT AND DISCUSSION****Overview of Photocatalytic Experiment**

The primary goal of the photocatalytic experiment was to evaluate the degradation efficiency of organic dyes (e.g., methylene blue) under UV and visible light using induced ZnO nanoparticles. The ZnO nanoparticles were synthesized using the sol-gel method, and doping with metal ions was employed to enhance the photocatalytic activity, particularly under visible light. The degradation was monitored by measuring the absorbance of the dye solution using UV-Visible spectroscopy.

Despite the theoretical improvements expected from doping ZnO nanoparticles, the photocatalytic experiments did not yield the desired degradation results. The absorbance of the dye solution remained relatively constant throughout the experiment, indicating limited or no significant photocatalytic degradation of the dye.

**Absorbance Behavior During Photocatalysis**

The absorbance of the dye solution was measured over time using UV-Vis spectroscopy to track the degradation process. Ideally, a significant reduction in absorbance at the characteristic wavelength of the dye (e.g., 365 nm for methylene blue) would indicate successful degradation. However, in this case, the following results were observed:

**Initial Absorbance:**

At the beginning of the experiment, the dye solution showed a strong absorption peak at 365 nm, corresponding to the presence of methylene blue



| Concentration | Absorbance |
|---------------|------------|
| Blank         | 0.0        |
| 0.01          | 0.320      |
| 0.02          | 0.525      |
| 0.03          | 0.992      |

Table 1: Concentration and Absorbance before addition of ZnO and sun light exposure

**Absorbance Over Time:**

After exposing the dye solution to UV and visible light in the presence of ZnO nanoparticles, the absorbance did not decrease as expected. Instead, the absorbance remained largely unchanged over the course of 120 minutes, indicating that the photocatalytic degradation process was ineffective.

| Concentration | Absorbance |
|---------------|------------|
| Blank         | 0.0        |
| 0.01          | 0.322      |
| 0.02          | 0.528      |
| 0.03          | 0.996      |

Table 2: Concentration and Absorbance after addition of ZnO and sun light exposure

**Possible Reasons for Limited Photocatalytic Activity**

Several factors could have contributed to the limited photocatalytic activity of the ZnO nanoparticles in this experiment:

- Insufficient Doping Concentration:** The concentration of the dopant may not have been optimal. If the doping concentration is too low, the modification of the ZnO band structure may be insufficient to enhance visible light absorption or to improve charge separation.
- Recombination of Electron-Hole Pairs:** High rates of recombination between photogenerated electron-hole pairs could significantly reduce the photocatalytic efficiency. If the recombination process occurs too quickly, the electrons and holes are not available to participate in redox reactions with the dye molecules.
- Particle Aggregation:** During the synthesis of ZnO nanoparticles, agglomeration of particles may have occurred, reducing the effective surface area available for photocatalytic reactions. This could limit the interaction between the dye molecules and the ZnO surface, leading to poor degradation performance.
- Poor Light Absorption in the Visible Range:** Although doping was intended to reduce the bandgap of ZnO nanoparticles, the red shift in the absorption spectrum may not have been sufficient to enable effective photocatalytic activity under visible light. The nanoparticles may still be primarily active under UV light, which would limit their usefulness under visible light conditions.
- pH and Reaction Conditions:** The pH of the dye solution can significantly affect the photocatalytic performance of ZnO. In this experiment, if the pH was not optimal for ZnO catalysis (typically around 9-10), the degradation efficiency could be negatively impacted. Additionally, insufficient stirring or uneven light distribution during the experiment may have contributed to the poor results.
- Impurities or Contaminants:** The presence of impurities in the reaction solution or on the surface of ZnO nanoparticles could have hindered the photocatalytic reaction by blocking active sites or interfering with the light absorption process.

**Analysis of Characterization Results**

The structural and optical characterization of the induced ZnO nanoparticles, as discussed in previous sections, revealed that the nanoparticles had a hexagonal wurtzite structure, with average particle sizes between 20 and 50

nm. The UV-Vis spectra showed a red shift in the absorption edge after doping, suggesting that the bandgap had been reduced. However, this shift may not have been sufficient to significantly enhance visible light absorption, especially under the experimental conditions used.

Photoluminescence (PL) analysis showed relatively strong emission peaks, indicating that electron-hole recombination was occurring at a high rate. This is consistent with the limited photocatalytic activity observed in the degradation experiments.

### Improvement Strategies

To improve the photocatalytic performance of the induced ZnO nanoparticles, several modifications could be considered in future experiments:

1. **Optimize Dopant Concentration:** Fine-tuning the concentration of dopants can help achieve a balance between reducing the bandgap and maintaining the structural integrity of the ZnO nanoparticles. Higher dopant concentrations may further reduce the bandgap, but excessive doping can introduce defects that act as recombination centers.
2. **Surface Modification:** Surface modifications, such as coating the ZnO nanoparticles with organic or inorganic materials, could improve the dispersion of particles and prevent agglomeration, increasing the active surface area available for photocatalytic reactions.
3. **Use of Electron Scavengers:** Adding electron scavengers to the reaction mixture can help prevent the recombination of electron-hole pairs, thereby enhancing the photocatalytic efficiency of the ZnO nanoparticles.
4. **Improved Reaction Conditions:** Optimizing the pH, light intensity, and reaction time may lead to better photocatalytic performance. In particular, operating at alkaline pH levels may improve the interaction between the dye molecules and the ZnO surface.
5. **Co-catalysts:** Incorporating co-catalysts, such as titanium dioxide (TiO<sub>2</sub>) or graphene, can enhance the photocatalytic activity of ZnO nanoparticles by improving charge separation and increasing the number of active sites for reactions.

## V. CONCLUSION

In this study, ZnO nanoparticles were synthesized via the sol-gel method, characterized, and tested for their photocatalytic efficiency in degrading methylene blue dye. The synthesis procedure was carried out successfully, producing ZnO nanoparticles with the expected hexagonal wurtzite crystal structure. Despite the successful synthesis and structural confirmation of the ZnO nanoparticles, their performance in photocatalytic degradation of methylene blue did not reach the desired level. The photocatalytic activity of ZnO is largely driven by its ability to generate electron-hole pairs under UV irradiation, which in turn produces reactive oxygen species (ROS) capable of degrading organic dyes like methylene blue. However, the experimental results showed that the degradation rate of methylene blue using the synthesized ZnO nanoparticles was lower than anticipated. Several aspects of the synthesis process and experimental setup may have influenced this outcome. While the ZnO nanoparticles exhibited the correct phase and morphology, the level of photocatalytic activity achieved suggests that the material's surface properties, crystallinity, or interaction with light and the dye molecules may not have been fully optimized. ZnO's wide bandgap (3.37 eV) typically makes it effective under UV light, but the response under visible light or less-than-ideal UV conditions may have limited the generation of sufficient reactive species for effective dye degradation. The experimental conditions, including the concentration of ZnO nanoparticles, the methylene blue dye concentration, and the pH of the solution, also play critical roles in the overall photocatalytic process. If these parameters were not fully optimized for ZnO's photocatalytic efficiency, they could have contributed to the lower-than-expected degradation results. Additionally, the surface area and particle dispersion are crucial for ensuring that ZnO has sufficient active sites for interacting with the dye molecules. Particle agglomeration, even though it wasn't highly pronounced in the characterization studies, might have further reduced the available surface area, thereby limiting the photocatalytic reaction. Future work should focus on optimizing the synthesis and doping process, improving the experimental setup, and investigating alternative strategies for enhancing the photocatalytic performance of ZnO nanoparticles under both UV and visible light. Despite the lack of desired results in this study, the potential of ZnO nanoparticles for environmental applications remains significant, and further research can help unlock their full capabilities.

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