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Photocatalytic Degradation of Methylene Blue Dye Using Zinc Oxide Nanoparticles under Solar Irradiation

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ABSTRACT

The discharge of synthetic dyes from textile and other industries colours water bodies and resists conventional treatment, and heterogeneous photocatalysis using semiconductor nanoparticles offers a means of degrading such dyes into harmless products using light. This paper reports the photocatalytic degradation of methylene blue dye using zinc oxide nanoparticles under solar irradiation. The degradation was studied as a function of irradiation time, with and without the catalyst, and the effects of the catalyst dose were examined, while the reaction kinetics were analysed. The results show that the dye was degraded efficiently in the presence of the zinc oxide catalyst under sunlight, with the degradation far exceeding that by photolysis alone, that the degradation increased with catalyst dose up to an optimum beyond which it declined slightly, and that the degradation followed pseudo-first-order kinetics. The study demonstrates that zinc oxide nanoparticles are an effective photocatalyst for the solar degradation of methylene blue and discusses the factors governing the process.

KEYWORDS: *Photocatalysis, Methylene Blue, Zinc Oxide, Dye Degradation, Solar Irradiation, Water Treatment, Reaction Kinetics*

INTRODUCTION

Synthetic dyes are used in large quantities by the textile, leather, and related industries, and their discharge into water bodies is a significant source of pollution, imparting colour, reducing light penetration, and resisting conventional biological treatment (5, 6). Effective methods for their removal are therefore needed.

Heterogeneous photocatalysis using semiconductor nanoparticles has emerged as an advanced oxidation process capable of degrading dyes into harmless products such as carbon dioxide and water, driven by light (1, 2). Zinc oxide is an attractive photocatalyst for this purpose, being efficient, inexpensive, and able to use sunlight (4, 8).

This paper reports the photocatalytic degradation of methylene blue dye using zinc oxide nanoparticles under solar irradiation. The effect of irradiation time, the role of the catalyst, the influence of catalyst dose, and the reaction kinetics are studied to evaluate the process (3, 9).

LITERATURE REVIEW

The principles and environmental applications of semiconductor photocatalysis have been reviewed comprehensively, beginning with the demonstration that illuminated semiconductors can drive chemical reactions (1, 2). The photocatalytic degradation of dyes proceeds through the generation of reactive species that oxidise the dye molecules (3, 10).

Both titanium dioxide and zinc oxide have been widely studied as photocatalysts, with zinc oxide showing comparable or superior activity for some dyes and the advantage of absorbing a broader range of solar radiation (4, 8). The parameters affecting the process, including catalyst dose, dye concentration, and pH, and the kinetics of degradation, have been extensively examined (5, 6, 7, 9).

Factors in Photocatalytic Degradation

The literature identifies several factors that govern the photocatalytic degradation of dyes (5, 6, 7). The principal ones considered here can be summarised as follows:

- The presence of the semiconductor photocatalyst.
- The irradiation time and light source.
- The catalyst dose, which provides active sites.
- The generation of reactive species that oxidise the dye.
- The reaction kinetics, commonly pseudo-first-order.

RESEARCH GAP

Although the photocatalytic degradation of dyes is well studied, concise investigations that compare degradation with and without the catalyst, examine the effect of catalyst dose, and analyse the kinetics together remain useful for demonstrating the process clearly under solar irradiation.

This study addresses that need by degrading methylene blue with zinc oxide nanoparticles under sunlight and evaluating these aspects.

OBJECTIVES

- To degrade methylene blue dye photocatalytically using zinc oxide nanoparticles under solar irradiation.
- To compare the degradation with and without the photocatalyst.
- To study the effect of catalyst dose on the degradation.
- To analyse the kinetics of the degradation reaction.
- To assess the effectiveness of zinc oxide as a solar photocatalyst.

METHODOLOGY

Aqueous solutions of methylene blue were treated with zinc oxide nanoparticles and exposed to sunlight, and the concentration of the dye was monitored over time from its absorbance. Experiments were conducted with and without the catalyst and at several catalyst doses, and the kinetics were analysed (3, 5).

Photocatalyst and Experimental Conditions

Zinc oxide nanoparticles were dispersed in methylene blue solution of known concentration, and the mixture was stirred and exposed to sunlight. Samples were withdrawn at intervals and their absorbance measured to follow the dye concentration, with control experiments performed without the catalyst, as summarised below (4, 8).

Table 1: Photocatalyst and Experimental Conditions

Parameter	Value
Photocatalyst	Zinc oxide nanoparticles
Dye	Methylene blue

Initial dye concentration	10 mg/L
Catalyst dose	0.5 to 2.0 g/L
Light source	Solar irradiation
Irradiation time	Up to 120 min

Kinetic Analysis

The degradation efficiency at each time was calculated from the decrease in dye concentration, and the kinetic data were fitted to a pseudo-first-order model by plotting the logarithm of the relative concentration against time. The rate constant was obtained from the slope, and the effect of catalyst dose on the rate was examined (3, 9).

RESULTS AND FINDINGS

The degradation of methylene blue as a function of irradiation time, with and without the zinc oxide catalyst, is shown in Figure 1. In the presence of the catalyst the dye was degraded efficiently under sunlight, whereas without the catalyst only slight fading occurred, demonstrating the photocatalytic nature of the process (2, 4).

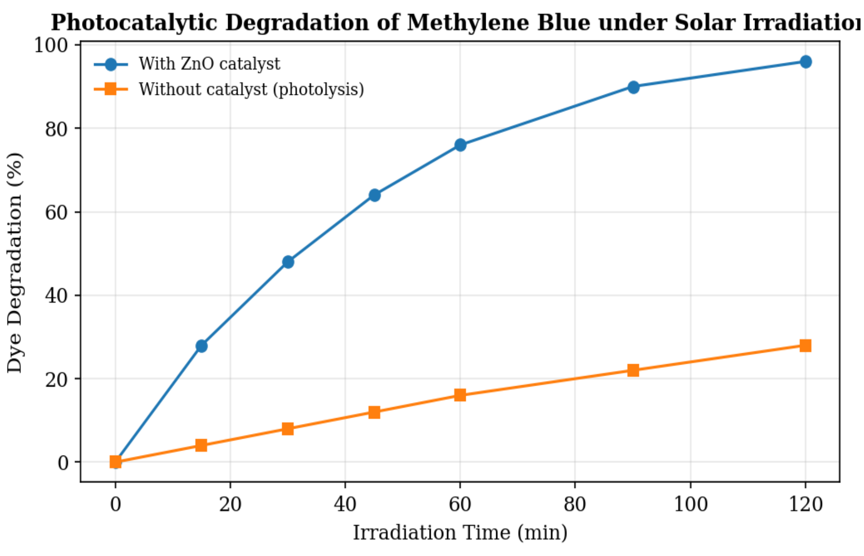

Figure 1: Degradation of Methylene Blue with and without the Zinc Oxide Catalyst

Table 2 reports the effect of catalyst dose on the degradation and rate constant, and Table 3 compares the degradation under different conditions with the kinetic fit. The degradation increased with catalyst dose up to an optimum, and followed pseudo-first-order kinetics.

Table 2: Effect of Catalyst Dose on Degradation

Catalyst Dose (g/L)	Degradation at 120 min (%)	Rate Constant k (per min)
0.5	82	0.0142
1.0	96	0.0258
1.5	93	0.0231
2.0	88	0.0198

Table 3: Degradation under Different Conditions

Condition	Degradation at 120 min (%)	Kinetic Fit (R^2)
Photolysis (no catalyst)	28	0.95
ZnO photocatalysis (optimum dose)	96	0.992
Dark adsorption (no light)	12	0.93

DISCUSSION

The results confirm that zinc oxide nanoparticles are an effective photocatalyst for the degradation of methylene blue under sunlight. The far greater degradation in the presence of the catalyst than by photolysis alone demonstrates that the process is genuinely photocatalytic, the illuminated zinc oxide generating reactive species that oxidise the dye, while the small degradation without catalyst and the limited dark adsorption confirm the central role of the illuminated catalyst (2, 4, 10).

The increase in degradation with catalyst dose up to an optimum reflects the greater number of active sites and reactive species available as more catalyst is added; beyond the optimum, the slight decline is attributed to increased turbidity and scattering of light, which reduce the effective illumination, a well-documented effect (5, 7). This identifies an optimal catalyst loading for efficient degradation.

The good fit of the data to a pseudo-first-order model is consistent with the kinetics commonly reported for the photocatalytic degradation of dyes at low concentration (3, 9). Together the results demonstrate that zinc oxide nanoparticles, using freely available sunlight, provide an effective and economical route to the degradation of methylene blue, with practical relevance to the treatment of dye-bearing effluents (6, 8).

CONCLUSION

This study demonstrated the photocatalytic degradation of methylene blue dye using zinc oxide nanoparticles under solar irradiation. The dye was degraded efficiently in the presence of the catalyst, far exceeding photolysis alone, the degradation increased with catalyst dose up to an optimum beyond which it declined slightly, and the reaction followed pseudo-first-order kinetics.

The findings establish zinc oxide nanoparticles as an effective and economical photocatalyst for the solar degradation of methylene blue, harnessing freely available sunlight. The process offers a promising route for the treatment of dye-bearing wastewater.

LIMITATIONS

- A single dye and photocatalyst were studied.
- Solar irradiation varied with natural conditions.
- The effects of pH and initial dye concentration were not examined in depth.
- Catalyst recovery and reuse were not assessed.

FUTURE SCOPE

- Evaluation of additional dyes and photocatalysts.
- Study of the effects of pH and initial concentration in detail.
- Investigation of catalyst recovery, reuse, and stability.

- Use of doped or composite catalysts to enhance activity.
- Assessment of degradation of real textile effluents.

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