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Research Paper

Photocatalytic Degradation of Diazinon in Aqueous Solutions Using ZnO Under Visible Light Irradiation: An Advanced Oxidation Process Approach

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Abstract
Diazinon is a commonly used organophosphate insecticide in agriculture, but its persistence in water and soil presents significant health and environmental concerns. This study investigates the photocatalytic removal of diazinon from aqueous solutions using zinc oxide (ZnO) nanoparticles activated by visible light irradiation. ZnO was chosen due to its excellent photocatalytic properties, including a direct band gap (∼3.1 eV), strong oxidative capability, chemical stability, and non-toxic nature, making it a superior candidate for visible-light-driven environmental remediation. Photocatalytic degradation under sunlight was also assessed for comparison. Key operational parameters, such as photocatalyst dosage, solution pH, initial diazinon concentration, and irradiation time, were systematically optimized. The highest degradation efficiency degradation was achieved with 20 mg of ZnO, neutral pH, 30 mg/L an initial concentration, and 60 minutes of irradiation. Kinetic analysis revealed that the process followed zero-order reaction kinetics ($k = 1.118$; $R^2 = 0.9962$). Notably, visible light irradiation was more effective than sunlight in degrading diazinon. These findings provide important details about the potential of ZnO nanoparticles as an efficient, low-cost, and environmentally friendly photocatalyst for remediating pesticide-contaminated water under sustainable energy conditions.

Keywords
Diazinon, Degradation, Photocatalytic, Zinc Oxide

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1. INTRODUCTION

The widespread use of pesticides in agriculture and industry has raised concerns due to their remarkable stability, which often prevents degradation under natural conditions. Consequently, these compounds can infiltrate environmental water resources, posing threats to ecosystems and human health (Mahmood et al., 2016; Pink, 2016). Globally, pesticide consumption has reached 2.36 billion kg, with 17% consisting of organophosphate pesticides, such as insecticides (Naimi Joubani et al., 2020). Insecticide pollution in surface and groundwater has become a significant environmental issue, making the removal of these compounds a key challenge (Khayat Sarkar and Khayat Sarkar, 2013). Diazinon, a phosphorothioate organophosphate, is commonly available in both granule and solution forms. It is widely used in Indonesia for crop protection and was previously employed for household pest control, targeting silverfish, cockroaches, and ants (Khoiriah et al., 2020). According to the World Health Organization (WHO), diazinon is classified as a moderately hazardous substance (Class II) (Jonidi-Jafari et al., 2017), and it demonstrates considerable toxicity to aquatic organisms at concentrations as low as 350 ng/L (Maleki et al., 2020). For humans, its lethal dose is estimated to range between 90 and 444 mg/kg body weight (Jonidi-Jafari et al., 2017). Diazinon also exhibits a moderate degree of mobility and persistence in soil, as reflected in its vapor pressure (1.4×10^{-4} mmHg at 20°C) and a low Henry's law constant (1.4×10^{-6} atm.m^3/mol) (Ghodsi et al., 2020), which limits its volatilization and reduces the risk of leaching into groundwater. Given these factors, addressing the remediation of diazinon-contaminated water systems is crucial to safeguarding human health.

Various techniques have been employed to eliminate diazinon, including adsorption, chemical coagulation, mag-

netic nanoparticles, biological methods, photocatalytic processes, precipitation, and oxidation processes (Jonidi-Jafari et al., 2015; Moussavi et al., 2013; Qin et al., 2016). Among these, advanced oxidation processes (AOPs) are particularly effective, as they can eliminate harmful compounds without generating polycyclic or aromatic byproducts (Mohammadzadeh Kakhki and Ahsani, 2020). AOPs are advantageous due to their ability to transform organic compounds into less harmful substances, potentially achieving complete mineralization of pollutants into CO_2 and H_2O in an environmentally sustainable manner (Munguti et al., 2023). Photocatalytic oxidation is a prominent subclass of AOPs, in which light energy activates a semiconductor material to generate electron–hole pairs that form highly reactive radical species (ROS), such as hydroxyl ($\bullet OH$) and superoxide ($\bullet O_2^-$) radicals, under light exposure. These radicals are responsible for the degradation of organic pollutants (Mohammadzadeh Kakhki and Ahsani, 2020). Thus, photocatalysis, especially using semiconductor metal oxides, is considered a practical AOP technique due to its ability to mineralize toxic compounds into benign end products using light as a clean energy source (Sajjad et al., 2018).

Semiconductor metal oxides like titanium dioxide, iron oxide, cadmium sulfide, zinc oxide, zirconium dioxide, and zinc sulfide have been widely investigated as photocatalysts due to their cost-effectiveness, optical activity, and stability (Mohammadi et al., 2020; Mohammadzadeh Kakhki and Ahsani, 2020; Sajjad et al., 2018). These oxides facilitate the generation of active oxidation radicals upon photon adsorption while preventing the regeneration of harmful byproducts during the process. Among them, zinc oxide (ZnO) is widely used as a photocatalyst for removing organic compounds due to its high light sensitivity, chemical stability, direct band gap, ability to decompose toxic organics, and capacity to absorb a broad spectrum of electromagnetic waves (Ong et al., 2018; Ramadhini et al., 2023). ZnO is particularly effective in absorbing photons across a significant portion of the UV light spectrum (Munguti et al., 2023). Daneshvar et al. (2007a) demonstrated that ZnO powder could degrade diazinon through a photocatalytic process using UV-C light irradiation, achieving 80% degradation within 80 minutes under optimal conditions. Most photocatalytic studies rely on UV lamps as the primary light source, yet UV light represents only about 3% of the solar spectrum compared to visible light's 44% (Lu et al., 2022). Moreover, UV light-driven photoreactors are often expensive and pose environmental concerns (Zhang et al., 2024).

In this study, we employed both artificial visible light (halogen lamp) and direct sunlight to evaluate photocatalytic performance under controlled and natural conditions. Although visible light from artificial sources requires energy input, it provides a reproducible reference baseline. In contrast, sunlight offers a sustainable and cost-effective alternative. This comparative design enables assessment of ZnO photocatalytic efficiency under practical and idealized illumination settings, thus supporting potential real-world applications. Recent studies have also demonstrated significant advancements in using ZnO-based photocatalysts under visible light for the degradation of organophosphorus pesticides (Baig et al., 2025; Premalatha and Rex, 2024; Sun et al., 2023). Compared to doped or composite systems, our work uniquely emphasizes the possible use of unmodified commercial ZnO under optimized visible light conditions for diazinon degradation, reinforcing the practicality and cost-efficiency of this approach.

2. EXPERIMENTAL SECTION

2.1 Materials

Zinc oxide (ZnO) powder served as the photocatalyst in this study. Hydrochloric acid (HCl) and sodium hydroxide (NaOH, ≥99%) were used to adjust the pH of the working solutions. All chemicals were analytical grade and procured from Merck without further purification. Diazinon 60 EC (600 g/L), a commercial pesticide manufactured by Petrokimia Kayaku (Indonesia), was used as the target contaminant, with distilled water as the solvent for solution preparation.

2.2 Methods

2.2.1 Characterization of ZnO Photocatalyst

The physicochemical characteristics of ZnO were analyzed using various techniques. Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDX) (Hitachi SU3500, EDAX Octane Pro) was utilized to examine surface morphology, particle size, and elemental composition. The crystal phase and structure were investigated through X-ray diffraction (XRD) using a Bruker D2 Phaser with Cu Kα radiation ($\lambda = 1.5406$ Å) across the 2θ range of 5° to 75°. Optical properties were assessed via UV-Visible spectrophotometry (Jasco V-730) in transmission mode within the 200-780 nm wavelength range. The optical band gap (E_g) was estimated using the Tauc plot analysis derived from absorbance data, which involves plotting $(\alpha h\nu)^2$ versus photon energy ($h\nu$), where α is the absorption coefficient calculated from absorbance using the relation $A = \alpha d$, with A as absorbance and d as the path length in cm. The extrapolation of the linear portion of the plot to the photon energy axis (x-axis) yields the E_g value. This method, although more commonly applied to diffuse reflectance data (UV-DRS), has also been used in transmission-mode UV-Vis analysis to provide approximate band gap values for nanoparticles (Ong et al., 2018; Premalatha and Rex, 2024).

2.2.2 Photodegradation Activity Experiment

Photodegradation experiments were performed in batch mode using a custom-built reactor illuminated by a 100 W halogen lamp (Philips) as the visible light source. A homemade photocatalytic reactor was used for the experiment, as shown in Figure 1. Photodegradation experiments using direct sunlight were conducted between 9:00 AM and 12:00 PM

in Karawang, West Java, Indonesia (6°19′S, 107°18′E), to compare the efficacy of sunlight versus artificial visible light. During the experimental period, the weather conditions were clear skies and minimal cloud cover. These environmental conditions were kept as consistent as possible across trials to minimize variability. A diazinon stock solution was prepared, and standard concentrations (10–60 mg/L) were used to construct a calibration curve at 247.5 nm using UV-Vis spectrophotometry. A 20 mL sample of diazinon is placed in a quartz beaker and undergoes a photodegradation process, with variations in different parameters applied throughout the experiment. Key parameters affecting the photocatalytic degradation were investigated, including pH levels (3, 5, 7, 9, and 11), initial diazinon concentrations (10, 20, 30, 40, 50, and 60 mg/L), catalyst dosages (0, 5, 10, 15, 20, 25, and 30 mg), and irradiation durations (0, 30, 60, 90, 120, and 150 min). After exposure, each sample was centrifuged at 4000 rpm for 5 minutes and filtered using a 0.45 μm membrane to remove ZnO particles. The residual concentration of diazinon was determined via UV-Vis analysis. The degradation efficiency was calculated using Equation (1) (Tehubijuluw et al., 2022):

$$\%\text{Degradation} = \left(\frac{C_i - C_f}{C_f}\right) \times 100\% \quad (1)$$

where C_i and C_f represent the initial and final concentrations of diazinon, respectively.

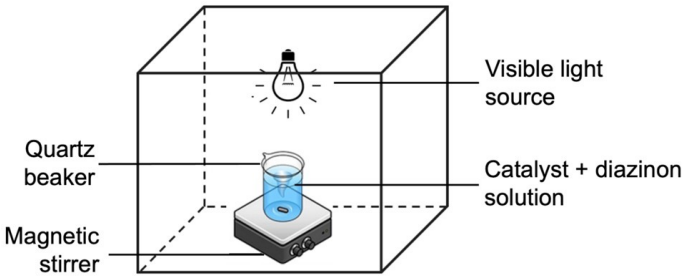

Figure 1. Schematic Representation of the Photoreactor Setup

All experimental conditions were maintained consistently throughout the study. However, due to limited access to materials and instrumentation, measurements for each parameter were conducted once. While this limits the statistical robustness of the results, future work will include multiple repetitions and statistical error analysis to ensure improved reliability and validation.

2.2.3 Kinetic Analysis

Kinetic modeling of diazinon degradation was performed using time-variant concentration data collected at 0, 30, 60, 90, 120, and 150 minutes under both sunlight and visible light irradiation. These data were fitted to three standard kinetic models: zero-order, first-order, and second-order. Linear regression analysis was applied to identify the best-fitting model based on the highest coefficient of determination (R^2). The corresponding rate constants were extracted to compare reaction rates under sunlight and visible light irradiation.

3. RESULTS AND DISCUSSION

3.1 The Properties of ZnO Photocatalyst

The UV-visible absorbance spectrum of ZnO depicted in Figure 2(a) indicates that ZnO typically absorbs light around the wavelength of 400 nm. This property is essential for visible-light-driven photocatalytic activity. The optical band gap (Eg) was determined using the Tauc method (Figure 2b), yielding an estimated Eg of 3.1 eV, consistent with typical ZnO characteristics and supporting its role as a viable photocatalyst under visible irradiation. The band gap energy, which indicates the energy needed to transition an electron from the valence band (VB) to the conduction band (CB), is an essential photochemical property, with bigger band gaps requiring greater energy for electron excitation (Premalatha and Rex, 2024).

Table 1. Kinetic Models and Their Associated Equations (Ghodsi et al., 2020)

Models	Equation
Zero-order	$C_0 - C_t = k \cdot t$
First-order	$\ln\left(\frac{C_0}{C_t}\right) = k \cdot t$
Second-order	$\left(\frac{1}{C_t}\right) - \left(\frac{1}{C_0}\right) = k \cdot t$

The surface morphology and composition of ZnO were characterized using SEM-EDX, as presented in Figures 3(a-c). The SEM micrograph in Figure 3(a) reveals that the ZnO nanoparticles exhibit a predominantly hexagonal structure with nanoscale dimensions, a typical feature of zinc oxide. The morphology indicated that the particles were mostly distinct, exhibiting minimal agglomeration. Figure 3(b) shows that the average particle diameter was measured at approximately 103.15 nm, confirming their classification as nanoparticles (Joudeh and Linke, 2022). Owing to their advantageous properties, such as chemical inertness, low toxicity, favorable optical/electronic characteristics, and high oxidative power, ZnO nanoparticles have been extensively utilized in photocatalytic degradation of pollutants (Maleki et al., 2020). Elemental composition analysis via EDX (Figure 3b) identified zinc and oxygen as the dominant constituents, comprising about 84.96% Zn and 15.04% O by weight. The diffraction peaks observed in Figure 3(d) at 2θ values of 31.7°, 34.4°, 36.2°, 47.5°, 56.5°, and 62.8° correspond to the (100), (002), (101), (102), (110), and (103) crystal planes, respectively, confirming the hexagonal wurtzite structure of ZnO. These findings align well with the standard ZnO pattern (JCPDS no. 36-1451) and are consistent with previously reported results Mamatha et al.

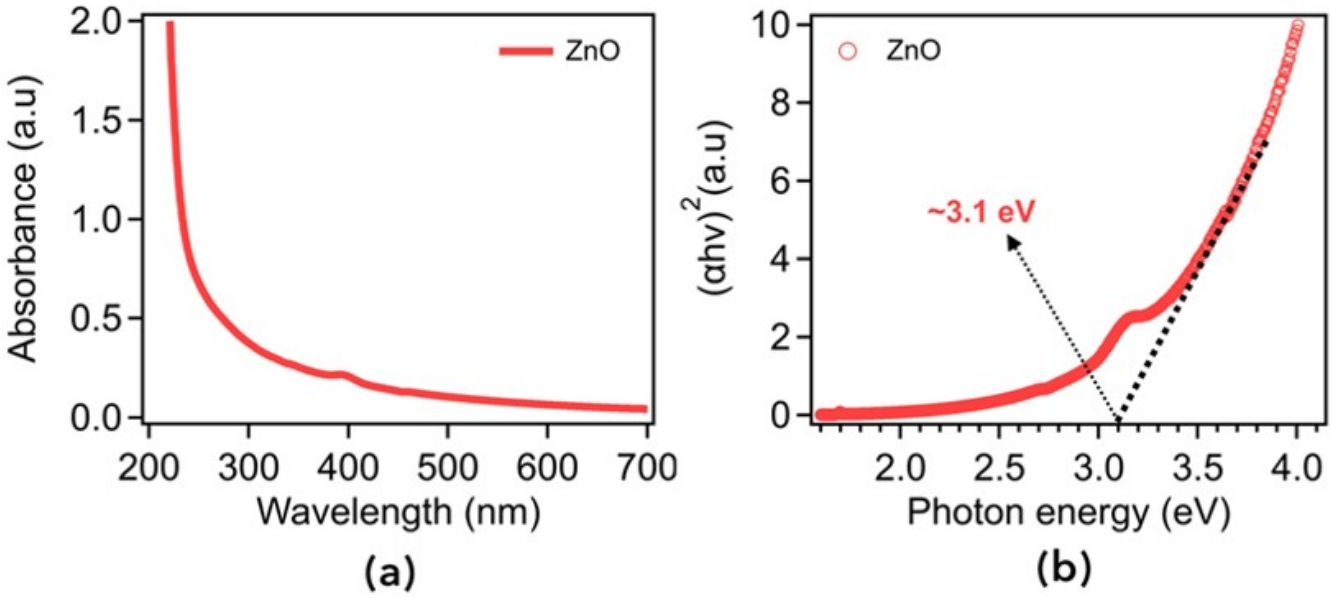

Figure 2. (a) UV-Vis Spectral, and (b) Tauc Plot for Determining the Optical Bandgap of ZnO

Table 2. Kinetic Model for Degradation of Diazinon

Kinetic Models	Sunlight Irradiation		Visible Light Irradiation	
	K	R^2	k	R^2
Zero-order	1.1325	0.9970	1.1186	0.9962
First-order	0.0082	0.9061	0.0086	0.8581
Second-order	0.0005	0.9654	0.0007	0.9436

(2022); Sridhar et al. (2023), further validating the hexagonal surface morphology observed in SEM images.

3.2 Standard Calibration Curve of Diazinon Solution

A standard calibration curve for the diazinon solution was established to derive a linear equation correlating absorbance values with diazinon concentration. According to the Lambe rt-Beer law, absorbance is linearly dependent on concentrations (Tehubijuluw et al., 2022). To ensure accuracy, sample dilutions were made as needed to keep absorbance values within the linear response range of the calibration curve. As illustrated in Figure 4, the resulting linear regression equation was $y = 0.0112x + 0.0043$, where y denotes the absorbance and x the concentration of diazinon. The correlation coefficient ($R^2 = 0.9985$) confirms a very strong linear relationship between absorbance and analyte concentration, validating the method for subsequent degradation analysis.

3.3 Photodegradation of Diazinon Measurement

3.3.1 Effect of Catalyst Dosage

This section evaluates how varying amounts of ZnO photocatalyst influence the degradation performance of diazinon. Different dosages ranging from 5 to 30 mg were applied under identical experimental settings. As depicted in Figure 5(a), diazinon removal efficiency improved with increasing ZnO dosage up to 20 mg. Beyond this point, further addition of catalyst led to a reduction in degradation for both light sources tested. The enhanced activity observed up to 20 mg is attributed to the availability of more active sites and a larger surface area, which facilitate pollutant adsorption, photon utilization, and the generation of reactive oxidative species like hydroxyl radicals (Kumar, 2017; Mohammadzadeh Kakhki and Ahsani, 2020; Noorimotlagh et al., 2014). However, when the ZnO photocatalyst dosage exceeded 20 mg, the degradation efficiency declined. This decrease is primarily due to catalyst aggregation, which reduces the accessible surface area and active sites (Kalantary et al., 2015). Additionally, a dense concentration of ZnO can increase turbidity, thereby diminishing photon accessibility to the catalyst surface (Jo et al., 2020; Kumar, 2017; Li et al., 2020). Excessive ZnO may also result in self-shadowing effects or deactivation through interparticle collisions between excited and ground-state atoms, emphasizing the importance of optimizing catalyst dosage to ensure

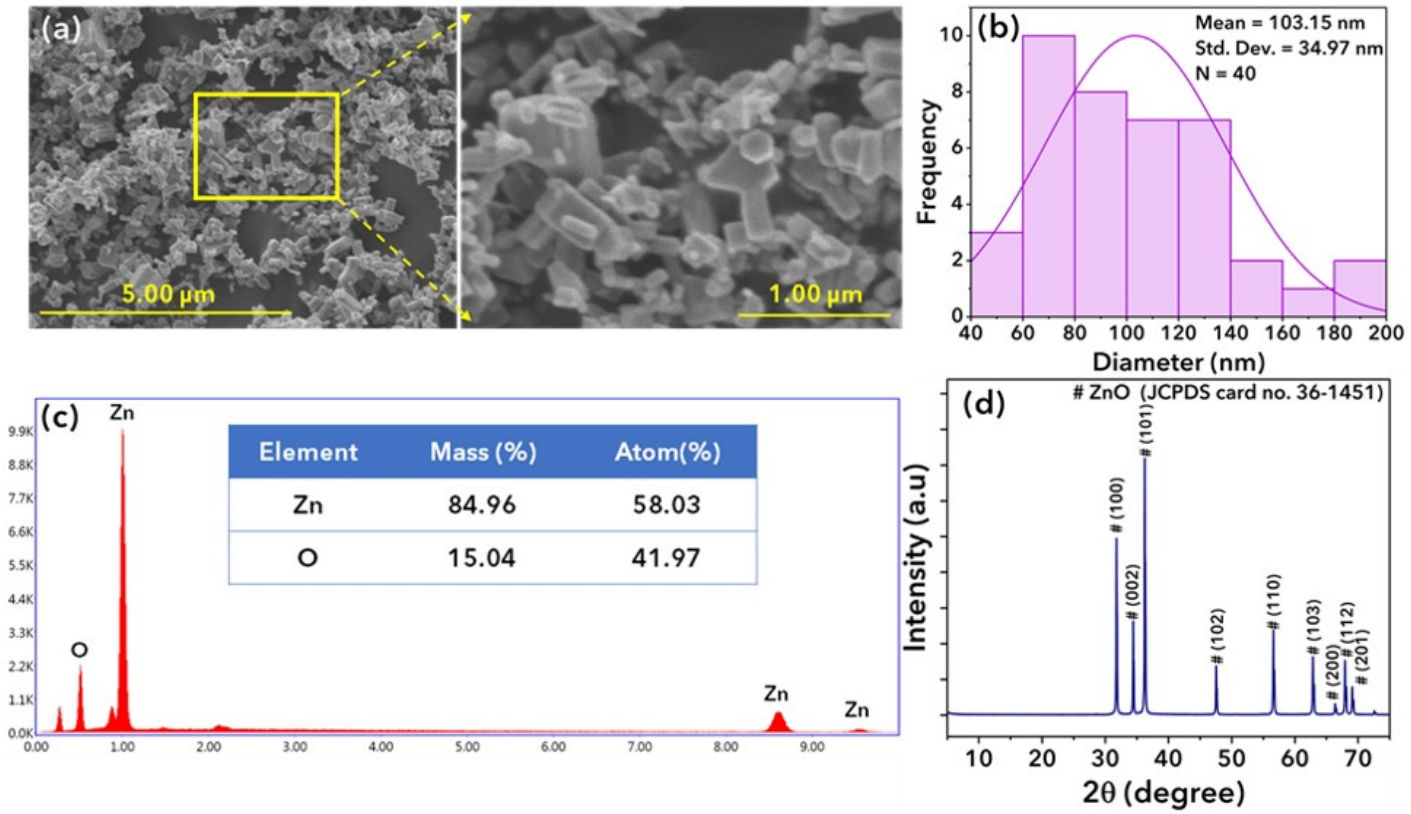

Figure 3. (a) SEM Image, (b) Particle Size Distribution, (c) EDX Spectrum of ZnO, (d) XRD Pattern of ZnO Nanoparticles

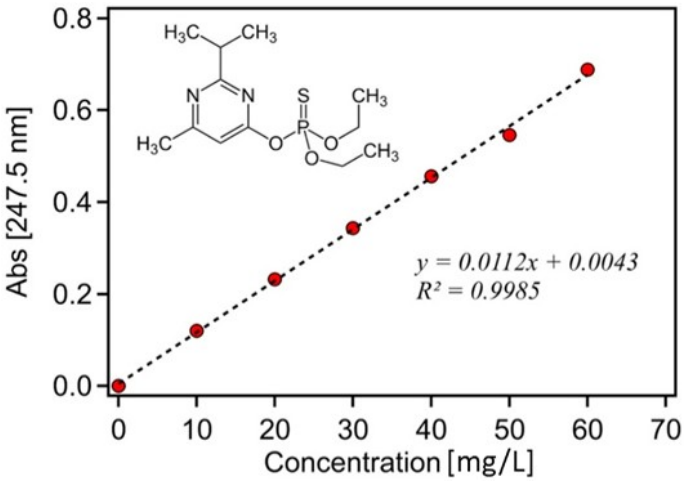

Figure 4. Standard Calibration Curve of Diazinon Solutions

efficient degradation (Munguti et al., 2023).

3.3.2 Effect of Initial Diazinon Concentration

The role of initial diazinon concentration on photocatalytic performance was assessed by adjusting its levels from 10 to 60 mg/L while maintaining the pH at 7 and using 20 mg of ZnO catalyst. As illustrated in Figure 5(b), a higher starting concentration of diazinon resulted in lower degradation efficiency. Under visible light exposure, degradation efficiency declined from 70.62% at 10 mg/L to just 16.78% at 60 mg/L after 60 minutes. A similar trend was observed under sunlight, where efficiency decreased from 51.96% to 8.49%. The reduced degradation efficiency at higher concentrations is likely due to competition between diazinon molecules for absorption on the ZnO photocatalyst surface. This condition restricts the generation of reactive species such as hydroxyl and superoxide radicals ($\bullet OH$ and $\bullet O_2^-$), which are essential for the oxidative degradation process (Kumar, 2017). Furthermore, excessive surface coverage by pollutant molecules can inhibit photon absorption and suppress radical formation, ultimately slowing down the reaction rate (Abramović et al., 2013; Chen et al., 2012; Maleki et al., 2020). Comparable observations have also been documented in previous literature (Nakaoka et al., 2010; Sakkas et al., 2005), confirming this concentration-dependent behavior.

3.3.3 Effect of pH Value

Figure 6(a) illustrates the impact of pH variation (3, 5, 7, 9, and 11) on the photocatalytic degradation performance of diazinon under fixed experimental conditions: 20 mg ZnO

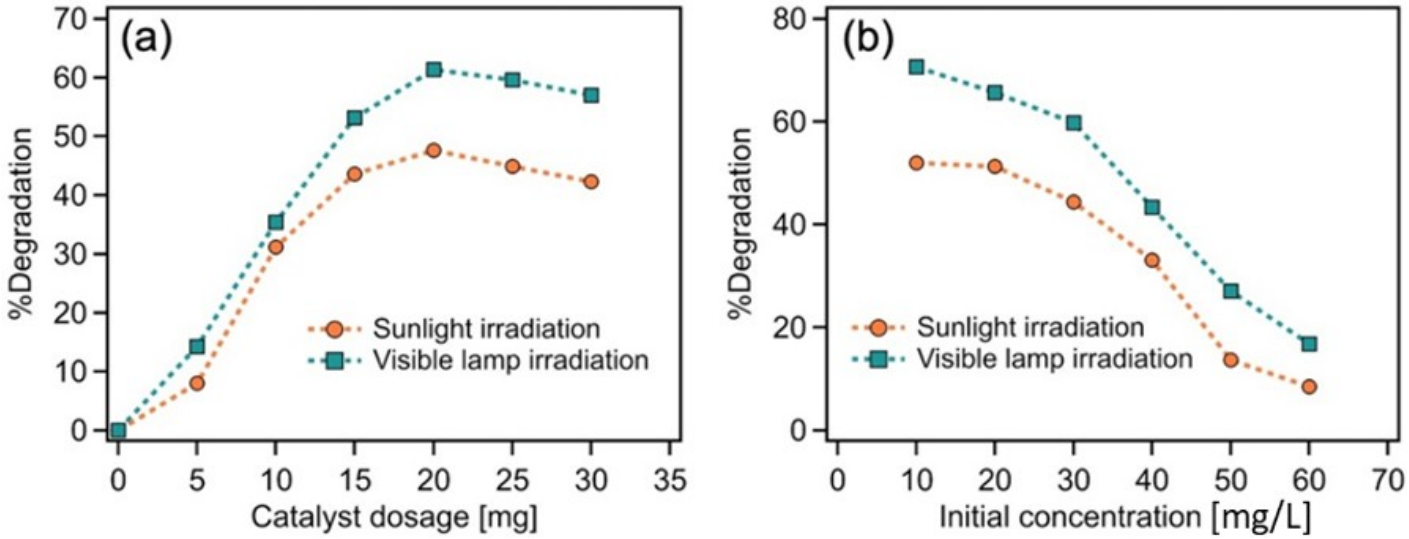

Figure 5. Effect of (a) Photocatalyst Dosage and (b) Initial Diazinon Concentration on the Photodegradation Process

catalyst, 30 mg/L diazinon concentration, and 60 minutes of exposure to either visible or natural sunlight. The results show that degradation efficiency increased as the pH rose from 3 to 7, reaching its maximum at the neutral pH. Specifically, diazinon removal peaked at 62.26% under visible light and 47.02% under sunlight at pH 7. This increase can be attributed to the electrostatic interaction between the photocatalyst surface and diazinon molecules. The zero-point charge (zpc) of the ZnO photocatalyst (pHzpc) is around pH 9 Daneshvar et al. (2007b), implying that the ZnO surface carries a positive charge in acidic to neutral conditions (<pHzpc) and becames negatively charged at values above 9 (>pHzpc). According to previous research, diazinon has a pKa of 2.6, making it negatively charged at pH values above this threshold (Khoiriah et al., 2020). Optimal photocatalytic activity occurs when the solution's pH is between 2.6 and 9, where diazinon (negatively charged) is electrostatically attracted to the positively charged ZnO surface, enhancing adsorption and subsequent degradation. At higher pH values, both diazinon and the photocatalyst become negatively charged, leading to repulsion and reduced photocatalytic efficiency (Mohammadi et al., 2020). Therefore, this study concludes that pH 7 provides the optimal conditions for diazinon degradation.

3.3.4 Effect of Irradiation Time

Time is a critical variable that directly affects degradation efficiency. This study explored the photocatalytic degradation process over a duration ranging from 0 to 150 minutes, using a constant ZnO photocatalyst dosage of 20 mg, pH 7, and an initial diazinon concentration of 30 mg/L under both visible light and sunlight irradiation. Figure 6(b) shows that diazinon degradation steadily increased with longer exposure times in the photocatalytic process. Initial measurements at 0 minutes (without light exposure or catalyst) showed minimal degradation, confirming that neither light exposure nor the catalyst alone is sufficient for effective degradation. Diazinon degradation under sunlight irradiation ranged from 10.71% to 67.29%, while under visible light, it increased from 20.23% to 74.94%, with exposure times from 30 to 150 minutes. The prolonged interaction between photons and the ZnO photocatalyst results in the generation of more active radical species, thereby enhancing the degradation of diazinon (Safitri et al., 2017). Additionally, the reactivity between reactive species and diazinon molecules improves with extended irradiation. The results indicate that during the first 30 to 60 minutes, the degradation rate increased more sharply compared to later intervals; however, the degradation efficiency gradually declined over time.

3.3.5 Kinetics of Photodegradation

The degradation behavior of diazinon was assessed by fitting the experimental concentration–time data to zero-, first-, and second-order kinetic models under both visible-light and sunlight conditions. All kinetic tests were performed at the optimized settings: pH 7, 20 mg ZnO catalyst, 30 mg/L initial pollutant concentration, and 60 minutes of irradiation. The mathematical expressions for each kinetic model are summarized in Table 1. Here, Co represents the initial diazinon concentration, Ct the concentration at time t, k the rate constant, and t the irradiation duration.

The linearity value of the kinetic models suggests that the photocatalytic degradation follows a zero-order reaction under both types of irradiations, as indicated by a higher regression coefficient compared to the other models (Table 2). The kinetic parameters were obtained by processing time-dependent degradation data. Regression analysis using concentration values at multiple time intervals confirmed that the degradation of diazinon followed a zero-order kinetic model under both light conditions, with R^2 values above

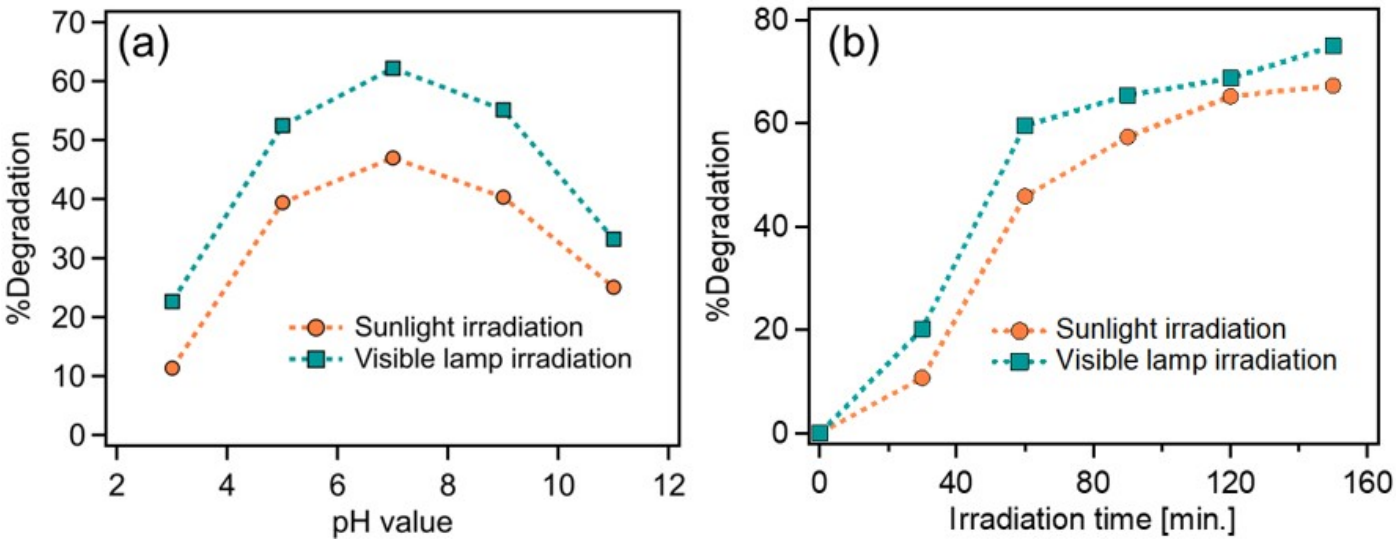

Figure 6. Effect of (a) pH Value and (b) Irradiation Time on the Photodegradation Process

Table 3. Comparison of Diazinon Degradation Achieved in This Study with Various ZnO-Based Photocatalysts Reported in the Literature

Photocatalyst	Light Source	Time (min)	Degradation (%)	References
ZnO/WO_3	Visible light	90	81.3	(Sajjad et al., 2018)
ZnO/Mn-rGO	Visible light	60	78.0	(Mohammadi et al., 2020)
ZnO/WO_3	Sunlight	120	83.0	(Maleki et al., 2020)
ZnO-(C,N,S)	UV light	100	53.4	(Hossaini et al., 2017)
ZnO/Co_3O_4-rGO	Visible light	140	99.6	(Mohammadi et al., 2023)
$ZnO-TiO_2$	UV light	120	99.9	(Jonidi-Jafari et al., 2015)
ZnO	Visible light	60	74.9	This Study

0.99. This indicates that the reaction rate is independent of diazinon concentration within the tested range.

In heterogeneous photocatalysis, the pseudo first order (PFO) kinetic model is frequently applied due to its mechanistic relevance under conditions where the catalyst is in excess relative to the pollutant. Although our data yielded the best statistical fit (R^2 >0.99) with the zero-order model, our findings could be attributed to the relatively high initial concentration of diazinon (30 mg/L), which may saturate the catalyst surface. Under such conditions, the reaction rate becomes independent of the diazinon concentration, leading to zero-order behavior, a phenomenon commonly observed in systems where catalyst surface saturation occurs at high pollutant concentrations (Daneshvar et al., 2007a; Kalantary et al., 2015).

3.3.6 The Comparison Type of Irradiation

All parameters in this experiment were studied under two distinct lighting conditions: direct sunlight and visible lamp irradiation. The results across all tested parameters consistently demonstrate that visible lamp irradiation leads to a higher degradation of diazinon than sunlight irradiation. The observed higher degradation under visible lamp irradiation is attributed to consistent photon flux rather than a fundamental difference in light energy. It is important to note that the ability of light to excite electrons across the band gap of ZnO (Eg ≈ 3.1 eV) depends primarily on the photon energy ($h\nu$), not the intensity. Only photons with energies equal to or greater than the band gap can initiate electron transition from the valence band to the conduction band. In this study, the visible halogen lamp consistently provided sufficient photon energy and stable exposure to exceed the activation threshold for ZnO, significantly enhancing the generation and concentration of electron-hole pairs (e^-/h^+), which is critical for the degradation process (Sun et al., 2023).

3.3.7 Photodegradation Mechanism of ZnO Photocatalyst

The degradation pathway observed in this study corresponds to the typical behavior of semiconductor-driven photocatalytic processes. With a band gap energy of approximately 3.1 eV, ZnO can absorb visible light at wavelengths below 400 nm, allowing excitation of electrons from the valence

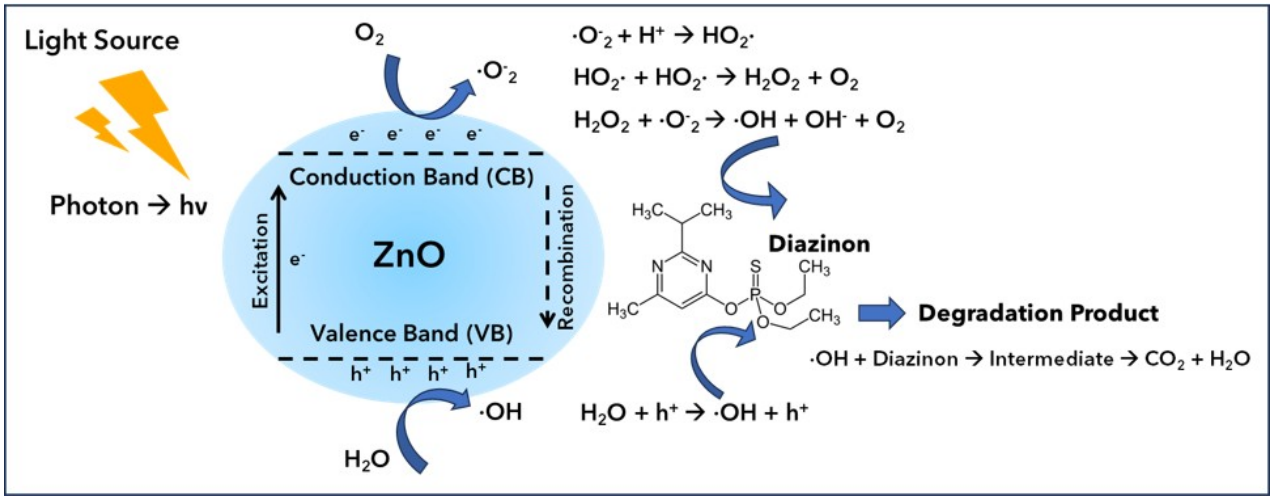

Figure 7. The Schematic Mechanism of Photocatalysis Using ZnO

band (VB) to the conduction band (CB). This transition generates electron–hole pairs, which are crucial to initiating surface redox reactions. Once formed, the excited electrons reduce molecular oxygen to generate superoxide anion radicals ($\bullet O_2^-$), while the corresponding holes oxidize water molecules or hydroxide ions, resulting in the formation of hydroxyl radicals ($\bullet OH$). Both reactive species are known for their strong oxidative capacity, playing a central role in breaking down diazinon molecules during the photocatalytic reaction (Abdullah et al., 2022). The higher degradation efficiency under visible light compared to sunlight can be attributed to the stable photon flux of the halogen lamp, which ensures continuous excitation of ZnO. This finding is further supported by the kinetic data, which revealed a zero-order reaction, suggesting that under our conditions, the catalyst surface was saturated with diazinon, and the reaction rate was governed by the availability of photon energy rather than pollutant concentration. Additionally, the SEM images confirming a hexagonal morphology and nanoscale size (∼103 nm) suggest a high surface-to-volume ratio, which enhances active site availability for photocatalytic reactions. These characteristics collectively support the proposed ZnO photocatalytic mechanism depicted in Figure 7 and reinforce the experimental observations made in this study.

To further highlight the novelty and positioning of this research, a comparison with previously published studies on ZnO-based photocatalysts is presented in Table 3. This comparative analysis includes information such as catalyst modification, light source, target pollutant, optimal conditions, and degradation efficiency. Unlike many studies that focus on doped or composite ZnO systems, our work uniquely utilizes unmodified, commercial ZnO and demonstrates significant photocatalytic performance under visible light without requiring additional sensitization. The result reinforces the practicality and cost-effectiveness of our approach for real-world applications, especially in rural or low-resource settings.

4. CONCLUSIONS

This study has demonstrated the promising potential of unmodified ZnO nanoparticles as a cost-effective and efficient photocatalyst for diazinon removal under both visible light and natural sunlight. The optimal conditions for degradation were identified as 20 mg ZnO, a neutral pH of 7, 30 mg/L diazinon, and 60 minutes of irradiation. Under these conditions, degradation efficiencies reached up to 74.94% under visible light and 67.29% under sunlight after 150 minutes. The reaction kinetics followed a zero-order model, suggesting a surface-saturated photocatalytic mechanism. Although ZnO is traditionally activated by UV light, our results confirm that it can be activated by visible light, which comprises a broader and more accessible portion of the solar spectrum. The enhanced performance under artificial visible light compared to sunlight is attributed to the consistent photon flux from the halogen lamp. Importantly, this work demonstrates that pristine, commercially available ZnO without any doping or structural modifications can still deliver competitive photocatalytic performance, making it a promising material for cost-effective and scalable water treatment applications. Future studies should focus on catalyst reusability, degradation by-product analysis, and performance validation under real wastewater conditions.

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