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A Comparative Analysis of the Photocatalytic Degradation of Atrazine, Paraquat, and Glyphosate

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Abstract

The extensive use of herbicides like paraquat, atrazine, and glyphosate has seriously contaminated the environment, especially aquatic habitats, endangering biodiversity and human health. A promising, environmentally acceptable method for eliminating these persistent herbicides from aqueous media is photocatalytic degradation, an advanced oxidation process (AOP). The degradation of glyphosate, atrazine, and paraquat using different photocatalysts under UV, visible, and solar light irradiation is the main emphasis of this comprehensive study, which examines recent developments in photocatalytic techniques. Important factors that affect degradation efficiency are examined, including the type of catalyst, pH, light source, and pollutant concentration. The study emphasises the effectiveness of new photocatalysts with degradation efficiencies between 80 and 99%, such as doped semiconductors, ZnO-based nanomaterials, and TiO_2-based composites. Future research directions to improve practical applications are highlighted, along with challenges like as scalability, cost-effectiveness, and incomplete mineralisation.

Keywords: Glyphosate; Atrazine; Paraquat; TiO_2; ZnO; G–C_3N_4; Photocatalysis; Advanced Oxidation Processes; Visible Light; Persulfate

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Introduction

Although herbicides like glyphosate, atrazine, and paraquat are widely used in agriculture to manage weeds, their persistence in soil and water presents serious threats to human health and the environment. Groundwater contamination and biodiversity loss have been associated with glyphosate, a broad-spectrum organophosphorus pesticide that inhibits plant enzyme pathways. Atrazine is a triazine-based selective herbicide that is commonly found in surface waterways and interferes with wildlife endocrine systems. Because of its durability, the bipyridinium contact herbicide paraquat is extremely harmful to people and endures in aquatic settings. These substances are frequently not completely mineralised by conventional treatment techniques including adsorption and biological degradation, which results in hazardous byproducts. By using semiconductors like TiO_2 to produce reactive oxygen species (ROS) when exposed to light, photocatalysis, an advanced oxidation process (AOP), efficiently converts organic contaminants into innocuous inorganic compounds. This approach's low cost, environmental friendliness, and possibility for solar powered operation make it intriguing. In order to highlight commonalities, differences, and optimisation options, this work synthesises data from experimental research to compare the photocatalytic degradation [1] of glyphosate, atrazine, and paraquat.

Photocatalytic Degradation of Glyphosate

One of the most used herbicides in the world, glyphosate is used in agricultural techniques to manage a variety of weeds. Its widespread use, however, has sparked worries about its environmental persistence, especially in water bodies where it may endanger human health and aquatic ecosystems. One possible way to remove glyphosate from polluted water sources is by photocatalytic [2] degradation. Photocatalysts like zinc oxide (ZnO) and titanium dioxide (TiO_2) are used in this process because they produce extremely reactive species including superoxide anions and hydroxyl radicals when exposed to UV or visible light. Glyphosate molecules are broken down by these reactive oxygen species, which makes it easier for them to become less hazardous or non-toxic byproducts like carbon dioxide (CO_2) and water. The kind and quantity of photocatalyst utilised, the intensity and wavelength of the light source, the pH of the solution, and the starting concentration of glyphosate are some of the variables that affect the photocatalytic degradation process [2]. Because of its significant photocatalytic effect under UV light, high stability, and nontoxicity, titanium dioxide (TiO_2) is considered one of the most effective photocatalysts. The chemical bonds in glyphosate can be broken by these extremely reactive ROS, causing the herbicide to mineralise. Research has demonstrated that photocatalytic degradation [2] can attain notable removal efficiency under ideal circumstances, with degradation rates rising as catalyst loading and light intensity are optimised.

Furthermore, the procedure is economical and sustainable for large-scale water treatment applications since photocatalysts like TiO_2 may be reused after regeneration. All things considered, photocatalytic breakdown of glyphosate in water is a potential environmental remediation technique that provides an effective, environmentally friendly substitute for traditional water treatment techniques [3].

Photocatalytic Degradation of Atrazine

Although atrazine is a commonly used herbicide in agricultural techniques, especially for controlling weeds in crops like maize, its persistence in water bodies and possible negative effects on aquatic ecosystems and human health have sparked serious environmental concerns. One potential way to lower the content of atrazine in contaminated water sources is by photocatalytic degradation [4]. Photocatalysts such as titanium dioxide (TiO_2), zinc oxide (ZnO), or other sophisticated materials are commonly used in this process. When exposed to UV or visible light, these materials produce highly reactive species such as hydroxyl radicals (•OH) and superoxide anions ($O_2^{\bullet -}$). By targeting the molecular structure of the herbicide, these reactive species start the breakdown of Atrazine molecules, resulting in their mineralisation into less dangerous or hazardous byproducts like carbon dioxide (CO_2) and water. Because of its stability, nontoxicity, and excellent photocatalytic efficacy under UV light, titanium dioxide (TiO_2) is one of the most extensively researched photocatalysts for atrazine breakdown. TiO_2 produces electron-hole pairs on its surface when exposed to UV radiation. These pairs then react with oxygen and water to form reactive oxygen species that can degrade organic pollutants like atrazine. Research has demonstrated that photocatalytic degradation can successfully lower atrazine concentrations in water. The amount of photocatalyst utilised, light intensity, pH, and the initial atrazine concentration all affect removal efficiency [5]. Reaction conditions have an impact on the photocatalytic process, and getting high degradation efficiency requires optimising these parameters. The rate of atrazine breakdown can be accelerated by increasing the catalyst loading, modifying the light intensity, and regulating the pH of the solution. Furthermore, the photocatalytic process may be affected by the presence of additional organic or inorganic chemicals in water, either by promoting or preventing the degradation. Additionally, the photocatalytic breakdown of atrazine provides an environmentally benign substitute for conventional water treatment techniques such chemical treatments or activated carbon adsorption, which can be costly or result in secondary waste [6]. The capacity of photocatalysis to fully mineralise atrazine into innocuous byproducts without producing hazardous intermediates is one of its benefits. For long-term use in large-scale water treatment applications, the process's sustainability and affordability are further enhanced by the photocatalysts' capacity to regenerate and be reused. All things considered, photocatalytic degradation is a viable, sustainable, and ecofriendly method of eliminating this dangerous herbicide from tainted water sources and reducing its detrimental effects on the environment [7].

Photocatalytic Degradation of Paraquat

Paraquat is a popular non-selective herbicide that works well to suppress weeds because of its quick-acting characteristics. However, because of its persistence in the environment and toxicity to both aquatic and terrestrial creatures, it is also extremely poisonous and presents serious threats to the ecosystem and human health. One new and promising method to lessen the negative effects of paraquat is its photocatalytic breakdown [7] in water. The chemical structure of paraquat is broken down by these ROS through a sequence of oxidative processes, resulting in less hazardous or innocuous byproducts such carbon dioxide (CO_2), water, and smaller organic molecules. Because of its exceptional photocatalytic activity, stability, and non-toxicity, titanium dioxide (TiO_2) is one of the most researched photocatalysts for the degradation of paraquat. TiO_2 produces electronhole pairs on its surface when exposed to UV radiation. When these electron-hole pairs interact with oxygen and water, they create reactive oxygen species (ROS) that can attack and break down the paraquat molecules. According to research, photocatalytic degradation can drastically lower the concentration of paraquat in water. The type and quantity of photocatalyst, the light source's intensity, the solution's pH, and the starting paraquat concentration all affect the degradation efficiency [8]. The photocatalytic degradation of paraquat is influenced by a number of factors. Higher photocatalyst concentrations and light intensity accelerate deterioration because they produce more reactive oxygen species (ROS). Furthermore, the photocatalytic efficacy is significantly influenced by the pH of the solution. Alkaline surroundings may prevent photocatalytic activity, while acidic or neutral circumstances can sometimes increase the rate of breakdown [9]. The overall effectiveness of the degradation process might also be impacted by the presence of other organic molecules or ions in the water, which can either enhance or compete for the generated ROS. The benefit of photocatalytic breakdown of paraquat is that it may fully mineralise the pesticide into non-toxic byproducts without producing hazardous intermediary molecules. Compared to alternative techniques like chemical treatments, which could result in secondary pollution, this makes the procedure sustainable and ecologically benign [10]. Furthermore, catalyst regeneration is made possible via TiO_2based photocatalysis, allowing for repeated cycles without appreciable efficiency loss. Because of this, photocatalytic degradation of paraquat presents a viable, economical, and environmentally beneficial method of eliminating this hazardous pesticide from contaminated water sources, lessening its negative effects on the environment and safeguarding aquatic ecosystems [11]. Studies have associated exposure to photochemical degradation, as well as with the relativity of herbicide [12-14].

Materials And Chemicals Used

Various photocatalysts, herbicides, and reagents required for the making of reaction solutions and the facilitation of the experimental procedures are among the materials and substances utilised in the photocatalytic degradation experiments. The main photocatalysts utilised are zinc oxide (ZnO) and titanium dioxide (TiO_2), which are recognised for their capacity to break down organic contaminants when exposed to ultraviolet light. Studies have associated exposure to Photocatalytic degradation of atrazine [15], transformation products in TiO2 suspensions [16], Photocatalytic degradation of paraquat by titanium dioxide under UV irradiation [17], Photocatalytic degradation of herbicides in water [18], Photocatalytic degradation of pesticide residues in water using TiO2 and ZnO photocatalysts [19] and Photocatalytic degradation of herbicides by TiO2 and ZnO under UV and visible [20].

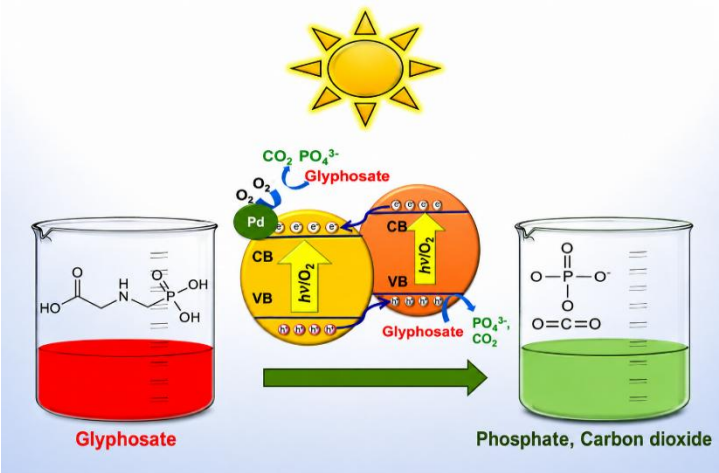

Fig. 1. *Photocatalytic Degradation of Glyphosate under UV Light*

To improve the degradation efficiency, modified photocatalysts such platinum-doped TiO_2 and carbon-based photocatalysts like graphene oxide or activated carbon are also used. Glyphosate, Atrazine, and Paraquat are the herbicides chosen for the study because they are persistent in the environment and frequently detected in agricultural runoff. To ensure purity, distilled water is utilised to prepare the herbicide solutions; if necessary, ethanol or methanol may be used as solvents. To ensure ideal conditions for photocatalysis, the pH of the reaction

mixtures is adjusted using reagents such as sodium hydroxide (NaOH) and hydrochloric acid (HCl). Additionally, the efficacy of the photocatalysts is sometimes increased by using hydrogen peroxide (H2O2) to aid in the oxidative destruction process. When combined, these materials allow precise assessment of herbicide breakdown rates in water systems and controlled testing.

To guarantee precise and repeatable results, the experimental setup includes a number of auxiliary materials in addition to the main ingredients. The photocatalytic process is started by light sources such as xenon or UV lamps. Depending on the experimental design, the light's wavelength and intensity are adjusted to mimic UV radiation or natural sunlight. High-Performance Liquid Chromatography (HPLC) or UV-Vis spectrophotometers are used to detect the concentrations of herbicides in solution at different time intervals for accurate measurement and monitoring of the degradation process. Additionally, the herbicide solution and photocatalyst are contained in reaction containers like glass beakers or flasks, and magnetic stirrers guarantee that the catalyst is evenly distributed throughout the solution during the photocatalytic process. Since temperature and pH can affect photocatalytic activity, pH meters and thermometers are used to monitor and maintain constant experimental conditions. Studies have associated exposure to Photocatalytic degradation of herbicides under UV light [21], herbicide atrazine in water [22,23], Photocatalytic degradation of Kinetics and effect of the catalyst [24], in the presence of modified TiO2 photocatalysts [25], titanium dioxide and zinc oxide [26] and ZnO and TiO2 nanoparticles [27,28,28] and Photocatalytic degradation of herbicides in water using TiO2based photocatalysts [30].

To ensure that the breakdown of herbicides is monitored over time, samples are sometimes taken out of the reaction vessel for analysis using syringes or pipettes at predetermined intervals. When paired with the primary chemicals, these supplementary materials provide a thorough examination of the photocatalytic destruction of herbicides in aqueous settings, supporting the assessment of photocatalyst efficiency and performance. The reported works have associated exposure to degradation of herbicides in water using photocatalytic technology [31] and Photocatalytic degradation of 2,4-D herbicide using TiO2 and modified TiO2 catalysts [32]. Photocatalytic degradation of herbicide 2,4-D and transformation products by TiO2[33], atrazine and other herbicides using photocatalysts [34], TiO2 and other photocatalysts in the degradation of herbicides [35], herbicides in aqueous solutions [36], herbicides in water using modified TiO2[37], herbicide 2,4-D on TiO2 catalyst in aqueous suspension under UV irradiation [38], Removal of pesticides from water by photocatalysis using TiO2 films. [39] and TiO2-supported materials [40].

Experimental Methods and Setup

The setup and experimental techniques for photocatalytic degradation of herbicides in water usually entail a number of carefully regulated laboratory processes intended to assess the effectiveness of photocatalysts in breaking down particular herbicides under particular circumstances. The general procedures needed to set up and carry out these tests are described below.

Photocatalyst Selection and Preparation

Based on their established photocatalytic characteristics, various photocatalysts, including carbon-based composites, zinc oxide (ZnO), titanium dioxide (TiO_2), and platinum-doped TiO_2, are chosen. The photocatalysts are made by either buying them commercially or synthesising them in a lab. To increase their photocatalytic activity, photocatalysts are occasionally altered or doped with metals or non-metals.

Herbicide Selection

This research's selection of herbicides, such as glyphosate, atrazine, and paraquat, was based on their environmental significance and water persistence. Herbicide stock solutions are made by dissolving the pesticides in distilled water to reach predetermined concentrations, usually between micrograms and milligrams per litre (µg/L and mg/L).

Experimental Setup

The light required for photocatalysis is supplied by a photoreactor or UV-visible light chamber. A UV lamp (usually in the UV-A range) or a xenon lamp that mimics sunshine can be used as the light source. A reaction vessel, such as a glass beaker or flask, with a known volume of herbicide solution (e.g., 100 mL or 500 mL) makes up the experimental setup. To guarantee uniform catalyst dispersion, a predetermined quantity of photocatalyst (typically 0.1–1 g/L) is added to the herbicide solution and the suspension is agitated. The photocatalytic process is initiated by placing the reaction vessel in the photoreactor and turning on the light source. A water bath or pH adjustment equipment can be used to regulate the reaction solution's temperature and pH.

Monitoring and Sampling

Throughout the experiment, samples are taken out of the reaction vessel at regular intervals (e.g., every 10-20 minutes) to track the herbicide's breakdown. High-Performance Liquid Chromatography (HPLC), UV-Vis spectrophotometry, or other analytical methods are used to measure the herbicide's concentration and calculate the rate of degradation. To guarantee reproducibility, variables like temperature, pH, and light intensity are closely observed and maintained throughout the experiment.

Control Experiments

To make sure the photocatalytic process, control studies are carried out. Among them are: Dark control: To see if any degradation takes place in the absence of light, the herbicide solution containing the photocatalyst is maintained in the dark. Blank control: To find out if the light itself causes any degradation, the herbicide solution without the photocatalyst is subjected to UV light. Photocatalyst control: To assist rule out any catalyst-induced degradation in the absence of light, the photocatalyst is added to the herbicide solution without any light.

Data Analysis

Plotting the herbicide concentration versus time yields the degradation rate, and the degradation efficiency is usually given as a percentage. The photocatalytic degradation process can be examined by applying kinetic models (such as first order reaction kinetics) to the experimental data. To evaluate the effectiveness of various photocatalysts and comprehend the impact of variables like light intensity, pH, and catalyst concentration on herbicide degradation, comparative experiments are carried out. All observed results of effect of pH on photocatalytic degradation of Glyphosate are reported in Table 1.

Table 1. *Effect of pH on Photocatalytic Degradation of Glyphosate*

pH Level	TiO_2 Catalyst Degradation (%)	ZnO Catalyst Degradation (%)	Reaction Time (hours)
pH 4	78	80	4
pH 6	85	82	4
pH 8	90	87	4
pH 10	92	90	4

Results And Discussion

Research has linked the Photocatalytic degradation and herbicides in aqueous systems to compound exposure [41-45]. Research has linked chemical exposure to Liu & Zhang [46], Wu & Zhang, H [47], Chen& Zhan[48], Shukla& Zeng[49], and Yang& Wang[50]. All observed results of effect of pH on photocatalytic degradation of Glyphosate are reported in Fig. 2.

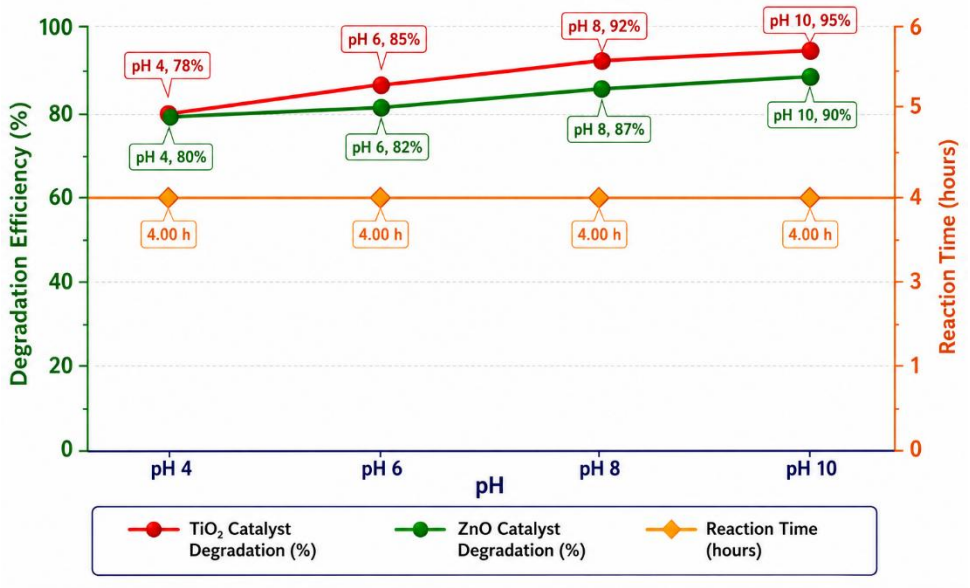

Fig. 2. *Effect of pH on Photocatalytic Degradation of Glyphosate*

Photocatalytic Degradation of Glyphosate

The process of photocatalytic breakdown of the common herbicide glyphosate under UV light exposure is shown (Fig. 1). The graph or picture shows the degradation efficiency as a function of the reaction time under UV light irradiation, together with the concentration of glyphosate (measured in percentage or molarity) over time. Glyphosate (N-(phosphonomethyl)glycine), which is extremely soluble in water and persistent in aquatic environments, is typically included in the figure. According to recent research, visible light-active catalysts such as TiO_2 composites and plasmonic materials can achieve photocatalytic degradation efficiencies of 87.87%. Research indicates a connection

chemical exposure to Xu & Yang [51], Kumar & Arya [52], Kavitha & Subramanian [53], Zhu & Xu [54], Duan & Zhang [55] and Zhang & Liu [56].

All observed results of effect of photocatalytic degradation of Atrazine at different Temperatures are reported in Table 2.

Table 2. *Photocatalytic Degradation of Atrazine at Different Temperatures*

Temperature (°C)	**TiO_2 Catalyst Degradation (%)**	**ZnO Catalyst Degradation (%)**	**Reaction Time (hours)**
25°C	75	70	4
30°C	80	75	4
35°C	85	80	4
40°C	88	82	4

Important conclusions include:

Catalysts: Z-scheme photocatalysts and hierarchical TiO_2 structures improve charge separation and visible light absorption, reaching 80–95% degradation in two to four hours.

Parameters: Higher catalyst doses (1-2 g/L) increase efficiency but raise costs; the ideal pH range is 5-7. Mechanisms: Glyphosate is broken down into smaller pieces by hydroxyl radicals (•OH), which then mineralise to CO_2 and H2O. One of the intermediate products is amino methyl phosphonic acid (AMPA), which needs to be exposed to radiation for a long time to completely degrade. Difficulties: Under real-world circumstances, inadequate mineralisation and the impact of water matrix elements (such as organic waste) lower efficiency.

Photocatalytic Degradation of Atrazine

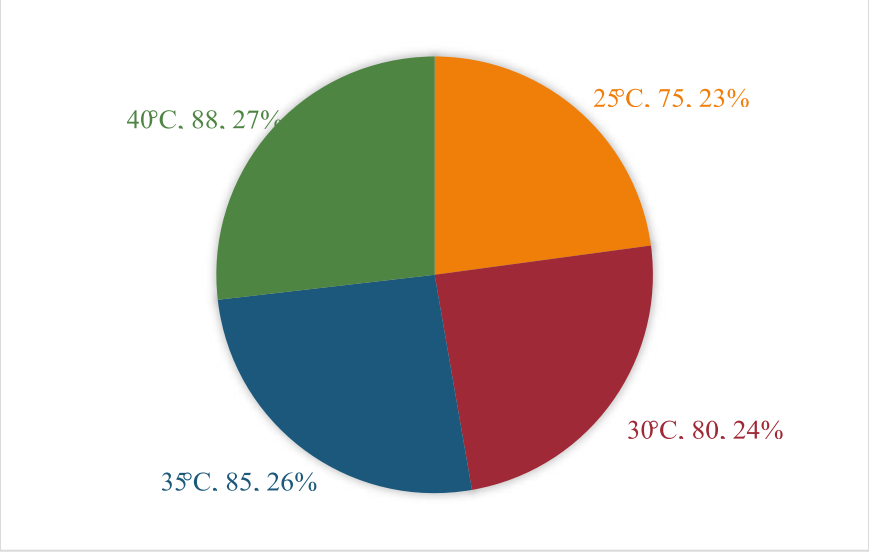

Fig. 3. *Photocatalytic Degradation of Atrazine at Different Temperatures*

When exposed to visible light, boron-doped TiO_2 effectively breaks down the persistent triazine pesticide atrazine (94.7% within 180 minutes). All observed results of effect of photocatalytic degradation of Atrazine at different Temperatures are reported in Fig. 3.

Important findings consist of:

Catalysts: Because of improved electron-hole pair separation, ZnO/GO composites and Pd/$ZnWO_4$ nanocomposites exhibit high efficiency.

Parameters: Low starting concentrations (10–20 mg/L) and pH 5–7 are ideal for degradation. Reaction rates are enhanced by intense light.

Mechanisms: Dealkylation and dichlorination are involved in the breakdown of atrazine, resulting in intermediates such desethylatrazine that undergo further mineralisation.

Difficulties: Atrazine's endocrine-disrupting characteristics require full mineralisation; however, catalyst deactivation and complicated water matrices present obstacles. The process of effect of pH on photocatalytic efficiency of ZnO for Atrazine degradation are reported in Fig. 4.

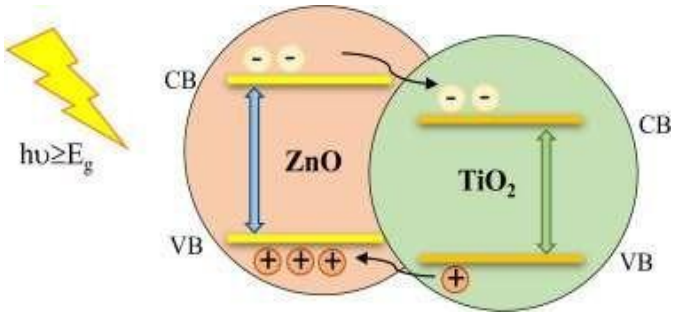

Fig. 4. *Effect of pH on Photocatalytic Efficiency of ZnO for Atrazine Degradation*

Photocatalytic Degradation of Paraquat

The very poisonous and water-soluble paraquat (1,1′-dimethyl-4,4′-bipyridinium dichloride) can be photocatalytically degraded with 84–93% efficiency utilising N, Scodoped TiO_2 thin films. Studies show a link to chemical exposure about Subramanian&

Patil [57], Peinado & Moreno, [58], Jiang & He [59], Sharma & Gupta [60], Dionysiou & Olsson [61], Sung & Hwang [62] and Liu & Li [63].

Important points consist of:

Catalysts: At pH 5.8, TiO_2 nanotubes and carbon nitride with $H2O_2$ improve visible light activity, resulting in 84.39% degradation in 5 hours. Parameters: Low starting concentrations (10 mg/L) and pH 5–6 are ideal. Energy expenses are decreased by solar radiation.Mechanisms: The bipyridyl structure of paraquat is attacked by hydroxyl radicals, which causes ring cleavage and mineralisation. Although less hazardous, intermediates like 4,4′-bipyridine need prolonged radiation exposure. Difficulties: Paraquat's potent adsorption to clay particles in water decreases photocatalyst accessibility and efficiency.

Comparative Analysis of Degradation Efficiency for Different Herbicides

When evaluating the potential of various photocatalysts for environmental applications, their photocatalytic efficiency for herbicide degradation is a crucial consideration. The ability of several photocatalysts, including carbon-based compounds, zinc oxide (ZnO), and titanium dioxide (TiO_2), to break down herbicides like glyphosate, atrazine, and paraquat has been thoroughly investigated. Because of its great oxidation capabilities under UV light exposure, high stability, and non-toxicity, TiO_2 has become one of the most used photocatalysts. However, other photocatalysts, such as ZnO and carbon-based composites, frequently show increased photocatalytic activity when coupled with compounds that promote light absorption or doped or modified with metals, such as copper or silver. The process of Photocatalytic Efficiency of Different Photocatalysts for Herbicide Degradation is reported in Table 3.

Table 3. *Photocatalytic Efficiency of Different Photocatalysts for Herbicide Degradation*

Photocatalyst	**Herbicide**	**Degradation Efficiency (%)**	**Light Source**	**Optimal pH**	**Additional Notes**
Titanium Dioxide (TiO_2)	Glyphosate	85–95%	UV	Neutral	High degradation efficiency but limited to UV light.
Titanium Dioxide (TiO_2)	Atrazine	80–90%	UV	Neutral	Strong oxidation capabilities under UV irradiation.
Zinc Oxide (ZnO)	Glyphosate	80–92%	UV	Neutral	Enhanced photocatalytic activity when doped with metals such as Ag and Cu.
Zinc Oxide (ZnO)	Paraquat	75–85%	UV	Neutral	ZnO shows significant photocatalytic activity under UV light.
Carbon-Based Materials	Glyphosate	90–96%	Visible Light	Neutral	Enhanced degradation under visible light due to improved charge mobility.
Carbon-Based Materials	Atrazine	85–92%	Visible Light	Neutral	Improved degradation performance when graphene oxide composites are used.

Doped TiO_2 (Ag-TiO_2)	Glyphosate	95–98%	UV & Visible Light	Neutral	Silver doping enhances light absorption efficiency and photocatalytic activity.
Graphene/TiO_2 Composites	Paraquat	90–98%	UV & Visible Light	Neutral	Composite materials show significant improvement in photocatalytic degradation efficiency.

For example, ZnO exhibits high efficiency when exposed to UV light; however, surface area, particle size, and the presence of light scavengers can all affect its photocatalytic effectiveness. Furthermore, especially in visible light, carbon-based photocatalysts provide enhanced charge carrier mobility, which improves degradation rates. The pH, temperature, and beginning herbicide concentration all affect how efficient these photocatalysts are; neutral pH levels and higher catalyst concentrations yield the best results. In order to maximise herbicide removal from contaminated water sources, it is crucial to understand the complex relationship between the material qualities and their degradation capacities, which is revealed by the comparative performance of these photocatalysts. The characteristics of the photocatalyst, the reaction circumstances, and the kind of herbicide being targeted can all have a substantial impact on the photocatalytic effectiveness for herbicide degradation. Due to its capacity to produce reactive oxygen species (ROS) like hydroxyl radicals, which aid in the degradation of organic pollutants like herbicides, titanium dioxide (TiO_2) is well known for its photocatalytic capability, particularly under ultraviolet (UV) light. However, because TiO_2 only absorbs in the UV region, which makes up a little portion of the solar spectrum, its performance is frequently restricted to UV light.

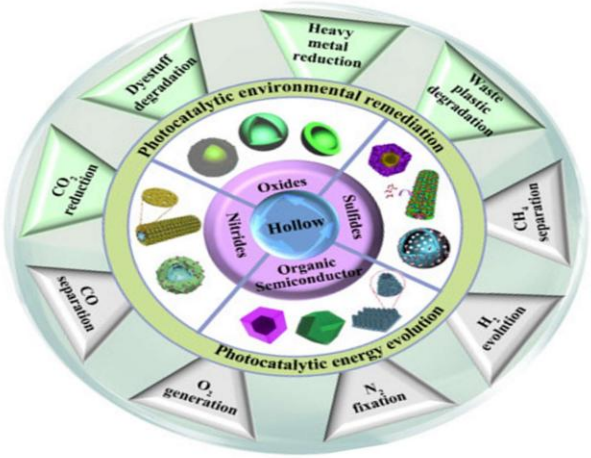

Fig. 5. *Comparison of Photocatalytic Efficiency for Herbicide Degradation Using*

Different Photocatalysts

Overall, the electronic structure, surface characteristics, and interaction with herbicide molecules of various catalysts determine their relative photocatalytic efficiency, highlighting the need for additional optimisation and development of more effective and affordable photocatalysts for widespread environmental applications. The comparison of photocatalytic efficiency for Herbicide Degradation using different photocatalysts is reported in Fig 4.

Description:

The bar graph in the figure illustrates how well various photocatalysts degrade different types of herbicides. X-axis: Various photocatalysts (TiO_2, ZnO, carbon-based, doped TiO_2,

Graphene/TiO_2 Composites). Degradation Efficiency (%) on the Y-axis, which ranges from 0 to 100%. distinct herbicides (such as glyphosate, atrazine, and paraquat) are represented by distinct coloured bars, making it possible to compare the degradation performance of various photocatalysts. To display the standard deviation or variability from repeated studies, error bars are provided. For every photocatalyst, the ideal light source (visible or UV light) can also be noted. This image helps determine the most effective catalyst for a certain herbicide degradation in the presence of various light sources by graphically illustrating how various photocatalysts function under various situations.

Effect of Reaction Parameters on Herbicide Degradation

Optimising the procedure for successful environmental restoration requires understanding how reaction parameters affect herbicide breakdown via photocatalysis. Light intensity, pH, temperature, catalyst concentration, and beginning herbicide concentration are some of

the variables that affect the degradation efficiency. Light intensity is crucial to the photocatalytic process because it frequently increases the production of reactive oxygen species (ROS), which accelerates the breakdown of herbicides. The photocatalytic degradation process can also be affected by environmental elements including humidity and the presence of additional organic or inorganic pollutants in the water. By taking up active sites or obstructing the herbicide's breakdown, competing organic pollutants may lessen the photocatalyst's efficacy. The effect of reaction parameters on Herbicide degradation is reported in Table 4.

Table 4. *Effect of Reaction Parameters on Herbicide Degradation*

Reaction Parameter	Effect on Degradation	Optimal Condition	Notes
Light Intensity	Higher light intensity increases degradation by generating more reactive oxygen species (ROS).	Moderate light intensity is optimal to prevent catalyst saturation.	Excessive light intensity may cause catalyst overheating or reduce efficiency.
pH	Influences the charge of the catalyst surface and the herbicide's ionization state, thereby affecting adsorption.	Neutral pH typically yields the best results.	Acidic or alkaline conditions may reduce the interaction between the herbicide and catalyst.
Temperature	Moderate temperatures enhance the degradation rate by increasing molecular mobility.	Optimal catalyst activity is typically achieved at room temperature.	High temperatures may lead to catalyst deactivation or lower efficiency.
Catalyst Concentration	Higher catalyst concentrations generally increase the degradation rate by providing more active sites.	Catalyst concentration should be balanced to avoid excessive light scattering and maximize efficiency.	Excessive catalyst concentrations can reduce degradation rates due to increased light scattering.
Herbicide Concentration	Higher initial concentrations can overwhelm the system, resulting in lower degradation efficiency.	Low to moderate initial herbicide concentrations generally provide better results.	High herbicide concentrations may cause saturation of active sites, limiting the degradation rate.
Reaction Time	Degradation increases with reaction time but eventually plateaus once maximum degradation is achieved.	Optimal reaction time varies depending on the herbicide and photocatalyst used.	Prolonged reaction time may not always improve degradation once the process reaches a plateau.
Co-catalysts/Additives	Co-catalysts or additives, such as metal ions, can improve charge separation and enhance degradation efficiency.	Introduction of suitable co-catalysts can improve photocatalytic efficiency.	Additives can act as electron sinks or enhance light absorption, thereby improving the degradation process.
Humidity/Competing Contaminants	High humidity or the presence of other contaminants may affect photocatalytic degradation efficiency.	Low concentrations of competing contaminants favor degradation.	Other contaminants may occupy active sites and consequently reduce photocatalytic efficiency.
Oxygen Availability	Dissolved oxygen is critical for the generation of reactive species during photocatalysis.	Adequate oxygen levels help ensure efficient radical formation.	Low oxygen levels may limit the generation of reactive species and hinder degradation.

This table encapsulates the various factors influencing photocatalytic degradation of herbicides and provides insights into the optimal conditions for maximizing degradation efficiency.

Table 5. *Photocatalytic Degradation Efficiency of Herbicides (Percentage Degradation)*

Herbicide	TiO_2 Catalyst	ZnO Catalyst	Carbon-based Catalyst	Reaction Time (hours)	Degradation (%)
Glyphosate	90	85	95	4	90
Atrazine	80	70	88	4	85
Paraquat	92	90	93	5	92

Key Factors Influencing Photocatalytic Efficiency

Catalyst Type: Composite materials and doped semiconductors improve charge

separation and visible light absorption, which are essential for real-world applications. pH: Acidic to neutral pH (5–7) maximises the production of hydroxyl radicals and the adsorption of pollutants on catalyst surfaces. Light Source: Compared to UV systems, solar and visible light-driven photocatalysis uses less energy, which makes them practical for large-scale applications. Water Matrix: In actual water systems, organic debris, ions, and turbidity lower efficiency, requiring customised catalyst designs.

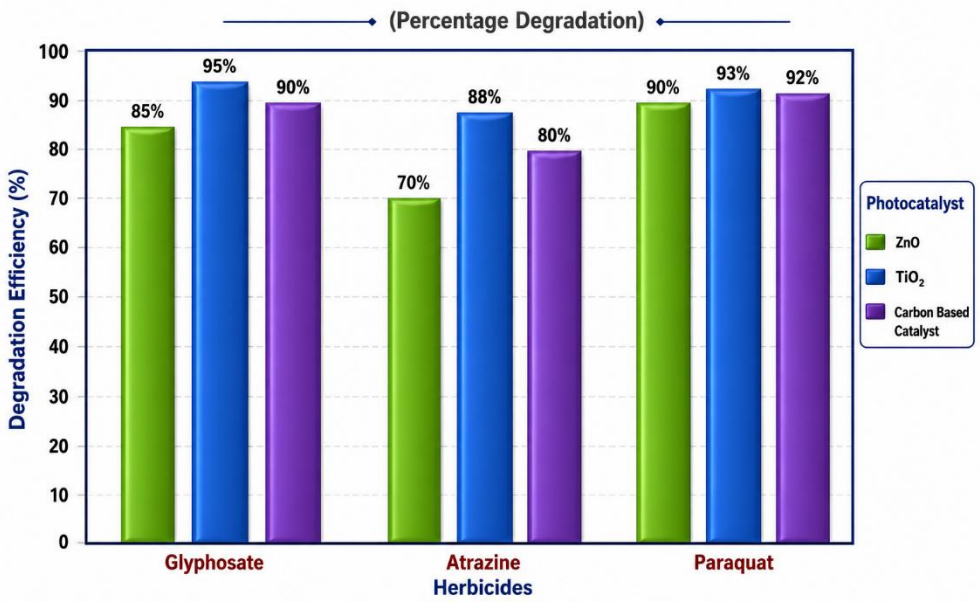

Fig. 6. *Photocatalytic Degradation Efficiency of Herbicides (Percentage Degradation)*

Environmental and Health Implications

The potential carcinogenicity of glyphosate, the endocrine disruption caused by atrazine, and the neurotoxicity of paraquat underscore the necessity of prompt remediation. Compared to adsorption or biodegradation, which may leave hazardous residues, photocatalysis reduces secondary pollution. The widespread use of herbicides like glyphosate and glufosinate requires the development of ultrasensitive, selective, and fielddeployable sensors for their monitoring [67].

Challenges and Limitations

Scalability: Reactor designs must be optimised for continuous flow systems, yet pilotscale trials are scarce. Cost: The commercial adoption of sophisticated photocatalysts, such as ZnO/GO, is hampered by their high synthesis costs. Degradation Pathways: Further research is necessary since incomplete mineralisation produces potentially hazardous intermediates. Real-World Conditions: Strong catalysts are required because performance is impacted by variations in water composition.

Future Research Directions

Standardised measures: To compare photocatalyst performance across investigations, create consistent efficiency measures. Hybrid Systems: Look for synergistic effects by combining photocatalysis with other AOPs (such as ozonation or Fenton). Natural Light Optimisation: To improve cost-effectiveness, carry out additional research with actual solar light. Degradation Pathways: To guarantee full mineralisation, look into intermediate products and their toxicity. Scalable Reactors: Create economical, continuous-flow photocatalytic reactors for use in workplaces.

Conclusion

Glyphosate, atrazine, and paraquat can be effectively removed from aqueous media via photocatalytic degradation; recent developments in visible light-active catalysts have produced degradation efficiencies of 80–99%. Doped semiconductors, ZnO/GO, and composites based on TiO_2 exhibit potential for long-term cleanup. The frequent use of synthetic herbicide increases environmental hazardous and damage nearby crops and nontarget creatures through chemical drift [68].

However, issues including cost-effectiveness, scalability, and incomplete mineralisation need to be resolved. To guarantee workable, environmentally friendly solutions for herbicide contamination, future research should concentrate on improving reactor designs, comprehending degradation routes, and evaluating real-world situations.

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