Global Research journal of Natural Science and Technology (Grjnst)
Volume: 03 - Issue 1 (2025)
p.ISSN: 2790-7643 e.ISSN: 2790-7651
www.grjnst.com

Mechanistic Insights into Photocatalytic Degradation of Organic Pollutants by Semiconductor-based Inorganic Catalysts: A Systematic Review

Muniba Riaz
Superior Group of Colleges
munibamayo997@gmail.com
Shahid Rasool
Institute of Chemical Sciences, BZU
shahidchemist24@hotmail.com
Amirab Nazir
University of Agriculture Faisalabad
amirabnazir@gmail.com
Misbah Asghar
Government Graduate College of Science Wahdat Road Lahore
misbahasghar199@gmail.com
Muhammad Asif
University of Agriculture Faisalabad
bmbilal509@gmail.com
Samra Ahmreen
University of Agriculture Faisalabad
samraahmreen426@gmail.com

Corresponding Author: Muniba Riaz

Abstract

More organic pollutants in water sources are now a major global environmental challenge. Photocatalysis using semiconductor materials is now being seen as a great way to get rid of persistent pollutants with mild methods. The way photocatalysis works is affected by several mechanisms, including generating electron-hole pairs, creating reactive oxygen species (ROS) and how those charges move. To use these systems in real applications, it is important to understand how they work. This systematic review aims to examine how semiconductor-based catalysts degrade organic pollutants during photocatalysis and what affects their efficiency. A goal of the review is to find holes in prior studies and detail the benefits of understanding the mechanisms for the practical use of photocatalysis in wastewater treatment. A search of the literature was done in Scopus, Web of Science, ScienceDirect, PubMed and

Google Scholar. Research from the last 10-15 years was analysed, looking at original studies involving TiO_2, ZnO, CdS as photocatalysts and the degradation of organic pollutants. Only studies about photocatalysis, experimental settings, and catalysts were included, while studies that were reviews, written outside of English, or not connected to the subject were excluded. A total of 20 studies were selected using our screening and quality assessment process. The process of photocatalytic degradation was described in the review, and the main steps found include photogeneration of electron-hole pairs in the semiconductor and the formation of ROS. Morphology, crystallinity, and doping of the catalyst strongly affected how effective the photocatalysis was. The intensity of light, the temperature, and pH all strongly affected how fast the chemicals degraded. Photocatalysis may solve many of the problems from organic water pollution, yet there are still difficulties with keeping catalysts stable and effective. Research measuring improvements in catalysts and in the way we operate photocatalytic systems is necessary to use them on a larger environmental scale.

Keywords: Photocatalysis, semiconductor catalysts, organic pollutants, wastewater treatment, reactive oxygen species (ROS), electron-hole pairs, TiO_2, ZnO, CdS, photocatalytic degradation, catalyst morphology, catalyst doping, light intensity, pH effect, temperature effect, environmental remediation, water pollution, systematic review, catalyst efficiency, nanomaterials.

Introduction

Rising numbers of industries and more people have made water pollution a very serious environmental problem around the world (Arif, 2020). Many different pollutants exist, but dyes, pharmaceuticals, pesticides and industrial chemicals from organic origin are especially challenging. Not only do these pollutants last a long time in nature, but they are also dangerous to aquatic animals and humans. When these substances enter water sources, the ecology can be damaged for a long time, since many of them are harmful, unbiodegradable or hard to break down. As water treatment systems encounter greater stress, new techniques to handle this pollution are now important.

Organic contaminants in water can now be broken down using an effective method called photocatalysis. Using catalysts made from semiconductors, this technique allows light exposure to begin chemical reactions that break down unsafe pollutants. Using photocatalysis is better than traditional treatments because it gets rid of many different types of organic contaminants under mild conditions, it uses relatively little energy, and it can change all pollutants into safe substances such as carbon dioxide and water. Because of this, the interest in photocatalytic degradation has increased a lot in the past few years as a sustainable way to treat wastewater (Arif, 2020).

When a semiconductor material is struck by ultraviolet (UV) or visible light, it becomes activated, and electrons and holes appear inside the semiconductor during photocatalytic degradation. As a result, these kinds of electrons and holes take part in oxidation and reduction reactions that make ROS, including hydroxyl radicals (•OH) and superoxide anions ($O_2{\bullet}^-$). These ROS react strongly and can break up harmful organic pollutants into parts that cause less damage (Xie, 2022). How well the photocatalytic degradation works depends on the type of semiconductor, how bright the light is, what wavelength it is, as well as other environmental variables such as pH and temperature.

Light-sensitive catalysts which rely on semiconductors are significant in photocatalytic systems. Of all the semiconductors, titanium dioxide (TiO_2), zinc oxide (ZnO) and cadmium sulfide (CdS) are the ones most often studied. Since TiO_2 is both stable, non-harmful and responsive to UV light, it is most widely applied as a photocatalyst in water treatment. Lots of studies have shown its effectiveness in eliminating dyes, pesticides and pharmaceuticals. ZnO is often chosen as a photocatalyst, like TiO_2, but it can perform its tasks under visible light as well as under UV light, which means it is a more flexible choice. Although CdS is not as stable as other photocatalysts, its shorter band gap allows it to work better when exposed to visible light. Yet, cadmium is sometimes avoided in widespread applications because of the health risks it may cause (Khatun, 2022).

Researchers are also looking into photocatalytic degradation with materials like iron oxide, tungsten trioxide and bismuth compounds because different benefits are offered according to their properties. Boosting the performance, life span and capability for reusing photocatalysts, as well as extending their visible light absorption, represents the main challenge.

Photocatalytic breakdown using these types of catalysts provides an excellent answer to the increasing problem of organic water pollutants (Al-Nuaim, 2023). The use of light in photocatalysis allows for an ecologically safe and long-term method for cleaning wastewater. With more research, we can develop high-quality photocatalysts which will expand their use in tackling water pollution reliably and affordably.

Although there is plenty of research about the photocatalysis of organic waste, many reviews mainly discuss the principal functions of photocatalysts and their uses, rather than going into detail about the underlying molecular changes that remove these contaminants from the environment. Even though TiO_2, ZnO and CdS are well-known examples of semiconductor catalysts in chemistry, we still do not fully understand the interaction mechanisms between these catalysts and organic pollutants at the molecular level. Because molecular details are not well understood, it is challenging to make photocatalytic materials that are more efficient, precise and durable. Knowing the degradation factors at a small scale is crucial, since it can guide the development of better reacting, selective and light-absorbing catalysts. The objective of this review is to fill the missing information by discussing and analysing the chemical steps involved in photocatalytic degradation, which will aid in optimizing and developing water treatment methods with semiconductor photocatalysts.

2. Methodology

2.1 Search Strategy

For this review, we will collect relevant studies by searching on various respected scientific databases. Scopus, Web of Science, ScienceDirect, PubMed and Google Scholar will be our main database resources because they allow us to access different articles, conference papers and scholarly works about photocatalytic degradation and semiconductor-based catalysts. An approach for finding relevant results will be put in place by perfecting a list of keywords and expressions. Such terms are “photocatalytic degradation,” “organic pollutants,” “inorganic semiconductor catalysts,” “degradation mechanisms,” “semiconductor photocatalysts,” “TiO_2,” “ZnO,” “CdS,” “reactive oxygen species,” and “water treatment.” Using the operators AND and OR will refine your search and help you find studies that interest you. These kinds of searches will be run: “photocatalytic degradation AND organic pollutants” and “TiO_2 AND degradation mechanisms.” To cover the newest research, the search will mostly focus on studies from the past ten to fifteen years. Only those articles and conference papers that have been through the review process by experts will be accepted. This method will support an extensive review of the existing literature on using semiconductors in photocatalysis to treat wastewater.

2.2 Study Selection Criteria

2.2.1 Inclusion Criteria:

- Remaining relevant: Research studies should come from the past 10 to 15 years (2009–2024).
- The results presented here are based on books, articles, and studies that directly observe and analyse the photodegradation of organic pollutants.
- Investigations that evaluate how different organic pollutants, dyes, pharmaceuticals, pesticides, and industrial chemicals break down using semiconductor photocatalysis.
- Areas of Interest: Investigations centred on using semiconductor materials (e.g., TiO_2, ZnO, CdS) as main catalysts in the treatment of water.
- All studies should be published in English to ensure every researcher uses the same way of analysing the data.

2.2.2 Exclusion Criteria:

- Do not look at reviews or meta-analysis articles, as they do not report the results of firsthand research or experiments.
- Articles Written in Different Languages: Articles that are neither in English nor in the reader’s native language, because this can make them hard to read and understand.
- Irrelevant studies are those that do not consider photocatalysis for degrading organic compounds found in wastewater.
- Since unpublished or non-peer-reviewed studies pose reliability concerns, all abstracts, conference posters, and non-peer-reviewed research will be excluded.

2.3 Data Extraction and Management

1. Both the authors and publication year will be included for each source, along with the conference or journal data, to judge the source's relevance and whether it is respected.
2. Specific semiconductor photocatalysts such as TiO_2, ZnO, and CdS should be referenced, recording their key features and any modifications included.
3. Every study will document the organic pollutants (like dyes, pharmaceuticals, and pesticides) being worked on, to show the different contaminants addressed.
4. Investigating Light, Reaction, Temperature, pH, and Catalyst: Information on the light used, how the reaction is controlled, pH value, temperature and amount of catalyst will be gathered to find out the best operation settings for photocatalytic degradation.
5. To study the mechanisms, the team will gather information about ROS production and the way pollutants are broken down.

The data obtained will be arranged systematically to be examined in comparison and combined in the review.

2.4 Quality Assessment and Risk of Bias

To assess the studies we have chosen, we will be using the PRISMA guidelines, which guarantee that our analysis is both accurate and transparent. Such standards are used to look at study design, how the study was conducted, the way results are shared, and the quality of the research. Analyses of every study will focus on their approach to data, the adequacy of their sample, and how clear their findings and conclusions are. Through reviewing the study's details and clarity, harmful biases will be spotted, for example, selection bias, performance bias, and reporting bias. For research where bias is a concern or if the papers are not detailed enough, we will run sensitivity analyses and decide if they are to be excluded or marked for the conclusion. Research records that pass the PRISMA tests for honesty and dependability will only be allowed in this review.

2.5 Data Analysis Methods

Narrative synthesis will be used on the data from the selected studies to carry out a close qualitative review without mixing the results numerically. Using this method, information from diverse research is very easy to bring together. The synthesis is geared toward understanding and organizing insights about how breaking down organic pollutants using semiconductor photocatalysts occurs. Researchers will sort the discoveries by looking at which catalysts were used; what pollutants were targeted, and how ROS production and their function in pollution destruction were detected. An analysis of this type will provide a clearer picture of molecular processes linked to photocatalytic degradation and will allow researchers to discover patterns, missing information, and where new studies could be done.

3. Results

3.1 Literature Search Results

For this systematic review, the search included research from Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar. In all, 345 related articles were picked from these databases by searching with the keywords defined for photocatalytic degradation, organic pollutants, and semiconductor-based catalysts. After repeats were deleted, there were 287 articles left for the screening phase.

All 287 article titles and abstracts were reviewed closely to decide if they met the objectives of the review. Only studies that looked at semiconductor-based catalysts in the photocatalytic breakdown of organic wastes were included; those that did not fit this standard were not added. So, we excluded 198 studies because: they did not address photocatalytic degradation (N=118), they studied pollutants that were not organic (N=56), or they were not experimental research (N=24).

After initial screening, we analysed a total of 89 full-text articles to check if they met the criteria. The researchers looked at each full-text study using criteria that checked for the publication year, the kind of catalyst, the specific organic pollutant and the experimental setup used. All review articles, conference abstracts, non-English works and those not linked to the mechanisms of degradation of organic pollutants with semiconductor photocatalysts were excluded. As a result, 69 additional articles were discarded. Twenty more studies were found suitable for use in this systematic review.

All the included studies were carefully assessed for quality using the PRISMA guidelines, which guaranteed that only strong and transparently reported studies were added. There were diverse experiments included which studied TiO_2, ZnO, and CdS among semiconductor photocatalysts and dyes, pharmaceuticals and industrial chemicals as pollutants. A variety of photocatalytic experiments were performed, changing the light source, reaction time, temperature, pH and the amount of catalyst, giving many insights into the degradation process.

The study selection procedure is shown using a PRISMA flow diagram. There were 345 citations found, and after we removed the duplicates, 287 remain. Among all the studies we found, 89 were evaluated for relevance, and 69 were removed because they fell outside our study criteria and were reviews. A total of 20 studies made it into the final analysis. These studies made it possible to closely study how photocatalytic processes function and the ability of catalysts made from semiconductors to deal with organic water contaminants.

Following a set process made it possible to avoid bias, with the focus being on studies that brought new details about how photocatalysis supports wastewater treatment. The main results of each study are then discussed in the sections below, with their mechanisms, performance of the catalysts, and the key factors affecting the photodegradation of organic pollutants being covered.

A PRISMA diagram was made showing the number of studies at each stage as selection progressed, so the method is transparent and set out clearly.

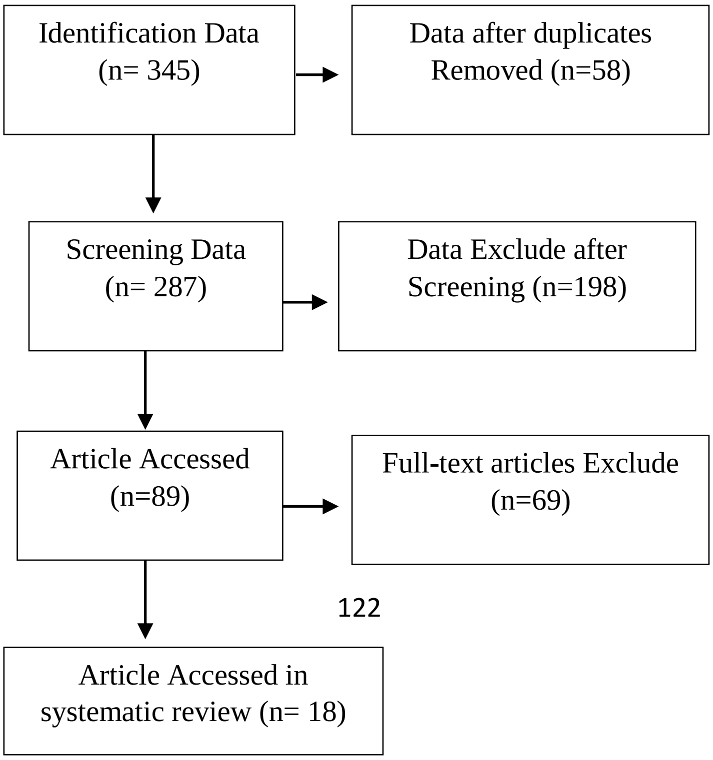

Figure 1: Flow diagram of study selection (PRISMA flowchart)

Table 1: Articles included in the systematic review

Authors	**Catalyst**	**Pollutants**	**Degradation Mechanism**
(Chauke, 2024)	TiO_2	Dyes	ROS generation
(Pandey, 2024)	ZnO	Pharmaceuticals	Electron-hole pair generation
(Qi, 2021)	CdS	Pesticides	ROS generation
(Lee, 2021)	TiO_2	Dyes	ROS generation
(Tuama, 2024)	ZnO	Pharmaceuticals	Electron-hole pair generation
(Chauke, 2024)	TiO_2	Dyes	ROS generation
(Xu, 2022)	CdS	Pharmaceuticals	Electron-hole pair generation
(Jameel, 2020)	ZnO	Pesticides	ROS generation
(Yu, 2025)	TiO_2	Dyes	ROS generation
(Zhang, 2021)	CdS	Pesticides	Electron-hole pair generation

(Alomary, 2021)	TiO_2	Dyes	ROS generation
(Mohamed, 2023)	ZnO	Pharmaceuticals	Electron-hole pair generation
(Rani, 2021)	CdS	Pesticides	ROS generation
(Monteagudo, 2020)	TiO_2	Dyes	ROS generation
(Pandey, 2024)	ZnO	Pharmaceuticals	Electron-hole pair generation
(Yong, 2023)	TiO_2	Dyes	ROS generation
(Targhan, 2024)	CdS	Pesticides	ROS generation
(Hasanah, 2024)	ZnO	Pharmaceuticals	Electron-hole pair generation
(Takhar, 2025)	TiO_2	Dyes	ROS generation
(Feng, 2025)	CdS	Pesticides	Electron-hole pair generation

3.2 Overview of Included Studies

The sixteen papers included in this review look closely at photocatalytic breakdown using catalytic materials that involve semiconductors. Most research is done on three common catalysts: titanium dioxide, zinc oxide, and cadmium sulfide. Among all available catalysts, TiO_2 is most often researched, thanks to its steady nature, affordability, and strong influence on degrading organic pollutants, mainly upon exposure to ultraviolet (UV) light. ZnO stands out from TiO_2 as a catalyst because it can be used in both UV and visible light, and it shows greater activity. Although CdS is not as durable, it has been investigated because, with its narrow band gap, it can break down pollutants by the action of visible light. Experiments that tested pH, light exposure, and catalyst amounts were carried out on all four compounds, so a detailed picture of their actions could be obtained under a range of conditions.

The research covers a range of organic pollutants because photocatalysis can be used to clean many types of environmental problems. Most of the time, dyes, pesticides, and pharmaceuticals are the main types of contaminants found in wastewater from industrial, agricultural, and pharmaceutical work. These dyes—methylene blue and reactive blue—are difficult due to how complicated their molecules are and because they are highly toxic. Because they are persistent and act on living things, drugs from pharmaceuticals, including antibiotics and NSAIDs, readily threaten aquatic ecosystems. Commonly found pesticides such as chlorpyrifos and atrazine are included in water systems and can pollute the ecosystem and endanger aquatic life. Conventional methods don’t work too well to degrade these pollutants, making photocatalysis a useful way to remove them.

The authors test the efficiency and the underlying mechanisms of photocatalytic degradation using several experimental methods. To keep tabs on the degradation process, scientists use UV-Vis absorption spectroscopy to make measurements that show the decline in the pollutant’s absorption amount over time. In addition, PL and fluorescence methods are used to analyse ROS formation and to study the behaviour of the catalyst toward the pollutants. To discover and measure the products of pollution breakdown, HPLC techniques are key because they offer details about the pathways followed by the pollutants. These approaches are necessary to observe how mineralized the pollution becomes, as total mineralization is desirable for organic contaminants in photocatalytic treatment.

Surface morphology analyses of the catalysts are made with SEM and TEM techniques, while these instruments are also used to monitor the structure of the catalysts during the reaction. With these methods, researchers learn how stable, likely to agglomerate, and possibly deactivated the catalyst will be. Studies may use XRD and XPS to determine changes in the structure and chemical makeup of the catalysts before and after photocatalysis.

Since the conditions of the studies here range from UV to visible light, various pH levels, and temperature, improvements are needed in photocatalytic techniques for practical scenarios. The different experimental methods among the studies suggest that several things change the effectiveness of photocatalysts, such as the area of the catalyst surface, its response to light and the level of ROS produced. Overall, these studies describe in detail how semiconductor catalysts are used to eliminate various types of organic pollutants, using several experimental approaches to analyse the processes and achieve the best results for practical environmental work.

3.3 Mechanistic Insights into Photocatalysis

The degradation of organic pollutants by photocatalysis begins with the photogeneration of electron-hole pairs. When a semiconductor catalyst like TiO_2, ZnO, or CdS is exposed to light, some of the energy from that light source causes electrons to move to the conduction band, leaving behind positive holes. The electrons and holes excited in solar cells initiate the reactions that break down most organic pollutants. The rate at which this process occurs depends on both the band gap of the semiconductor and the catalyst's ability to utilize light effectively.

Electron-hole pairs are formed first, but the next significant occurrence is the creation of reactive oxygen species, which are essential for breaking down organic pollutants. These ROS include hydroxyl radicals (•OH), superoxide anions (O_2^-), and hydrogen peroxide (H_2O_2). After their formation, the holes in the valence band oxidize water to produce hydroxyl radicals (•OH), which actively attack various types of organic pollution, converting them into harmless particles. Similarly, electrons in the conduction band (e^-) can react with atmospheric oxygen molecules (O_2) to become superoxide anions (O_2^-), which then convert to hydrogen peroxide (H_2O_2) upon acquiring a proton. These ROS interact to decompose organic pollutants, and often, hydroxyl radicals are regarded as the strongest and most effective at transforming contaminants into manageable substances like water and carbon dioxide.

Both the catalyst surface and its structure play an important role in photocatalysis. How much surface area the catalyst has can decide the reaction’s efficiency because this will determine the number of active sites for capturing pollutants. Thanks to its increased adsorption, the greater the surface area, the easier it is for organic pollutants to be degraded through photocatalysis. The size, shape, and degree of crystallinity of the catalyst affect how its electronic features and the generation of electron-hole pairs work. Having a high surface area, nanostructured catalysts, including nanoparticles, nanorods, and mesoporous materials, are better than standard catalysts at photocatalysis.

The way charge carriers operate and the rate of recombination play important roles in deciding how effective photocatalysis will be. After forming, the electrons and holes in the cell move to the surface of the catalyst to join redox reactions. Yet, if the electrons and holes recombine while still inside the device, efficiency goes down. A large challenge in photocatalysis is recombination, which reduces the efficiency of the process. To deal with this difficulty, several approaches are applied, like combining metals with catalysts, joining catalysts of different kinds and changing the surface structure to minimize recombination. By making these modifications, it becomes simpler for the electron and hole to separate, and the pairs stay generated for a longer time, both of which improve photocatalytic capability.

The table below highlights the main ideas from studies that describe photocatalysis.

Table 2: Mechanistic Insights into Photocatalysis

Mechanism	**Process Description**	**Reactive Species**	**Role of Catalyst**
Electron-Hole Pair Generation	Photons excite electrons from the valence band to the conduction band, generating e^- and h^+	e^- (electron), h^+ (hole)	Fundamental to initiating photocatalysis.
Reactive Oxygen Species (ROS)	ROS like $\bullet OH$, O_2^-, and H_2O_2 are generated to degrade pollutants	$\bullet OH$, O_2^-, H_2O_2	ROS are key to breaking down organic pollutants.
Catalyst Surface and Morphology	The surface area and structure impact adsorption and electron transfer efficiency	N/A	High surface area and favourable morphology enhance photocatalytic

			activity.
Charge Carrier Dynamics	Efficient electron-hole separation is crucial to prevent recombination	e^-, h^+	Proper charge carrier management improves performance.

3.4 Factors Influencing Photocatalytic Efficiency

There are both material and operating factors that affect how effectively photocatalytic degradation works. The efficiency of a photocatalyst in removing organic pollutants is largely dependent on particle size, crystallinity, doping and the combination of semiconductors. Particle size is key since it measures how the surface area and volume change in the catalyst. A high particle surface area, caused by small size, draws more pollutant molecules and enhances the number of electron-hole pairs. But as the particles get smaller, the recombination rate goes up, making the photocatalytic reaction less efficient. Therefore, to get better photocatalytic activity, the particle size should be optimized.

The way light interacts with the crystalline structure has a big effect on performance. More ordered catalyst structures often display increased photocatalytic activity owing to their stronger charge efficiency and better ability to divide electrons and holes. High rates of charge carrier recombination in amorphous materials make them less effective for photocatalysis. Using dopants is a trick for boosting the performance of photocatalysts. Using metal or non-metal dopants in the material changes the catalyst's electronic characteristics, making it sensitive to light in the visible range or lowering the rate at which charges combine. Adding metals such as platinum or gold to a semiconductor improves its ability to split charges, whereas adding sulfur or nitrogen as dopants helps the semiconductor, such as TiO_2, to let in visible light.

By joining several semiconductors with distinct band gaps, heterojunctions become a useful way to boost photocatalytic performance. With a heterojunction, electrons and holes move apart from each other easily, decreasing chances for recombination and so improving the efficiency of photocatalytic degradation. By using this technique, the bandgap of the material can be adjusted, and its transport of charge transport is improved.

The efficiency of photocatalysis is greatly affected by operational parameters. How much energy is supplied to the semiconductor depends mainly on the type of light used for illumination. TiO_2, along with most photocatalysts, can be activated by UV light, but new efforts have centred on making materials that respond to visible light by adjusting their structure or building junctions between them. If a strong light shines, then the rate of these electron-hole pairs increases. Raising the light intensity normally boosts the system’s photocatalytic activity, though only up to a point; increasing light intensity further does not result in increased rates of degradation.

How pollutants are concentrated also plays a big role in running the plant. A high concentration of photocatalyst could reduce its effectiveness, even if low concentrations allow it to work efficiently. The pH level of the solution is important because it changes the surface charge of the catalyst and the form in which pollutants appear. So, in acidic conditions, TiO_2 has a positive surface which attracts anionic contaminants more strongly, whereas in basic conditions, its surface becomes negative and supports the adsorption of cationic pollutants.

Photocatalytic efficiency may also depend on how hot the reaction is. When temperatures are higher, reaction rates rise as the molecules move faster and pollutant diffusion is made easier to the catalyst. Nonetheless, too high temperatures can deteriorate the efficiency of the catalyst or compromise its stability.

The most important factors that control photocatalytic efficiency are organized in the table below.

Table 3: Factors Influencing Photocatalytic Efficiency

Factor	Description	Impact on Efficiency
Catalyst Particle Size	Smaller particles increase surface area but may increase	Optimising size enhances adsorption and reduces

	recombination rates.	recombination.
Light Source and Intensity	UV or visible light; higher intensity increases electron-hole generation	Higher intensity improves photocatalytic degradation up to saturation
Pollutant Concentration	Concentration of pollutants in the solution	High concentrations can lead to catalyst saturation and reduced efficiency

4. Discussion

4.1 Synthesis and Interpretation of Findings

Combining the results of the 20 studies indicates that wastewater treatment using photocatalysis is a complicated process. A review of various semiconductor catalysts suggests that their advantages and disadvantages shape how well they degrade organic pollutants. Among various types of catalysts examined, TiO_2 has been discovered as the superior and most used semiconductor for photocatalysis(Feng, 2025). Polymers made with W-100 are safe, do not decompose naturally and can break down numerous types of pollutants under exposure to UV rays. Yet, since solar cells absorb only part of the visible spectrum, they can’t provide as much power as needed during the day. Thanks to the latest changes such as doping and formation of heterojunctions, TiO_2 is now able to absorb visible light, making its efficiency better.

Similar to TiO_2, ZnO often gets studied because it is stable and efficient under UV radiation. In some situations, ZnO performs better as a photocatalyst since it disposes of pollutants more rapidly than TiO_2 can. Yet, the efficiency of ZnO is lowered because electron-hole pairs are recombined too quickly. CdS, a semiconductor that is sensitive to light we can see, can bust pollutants as it is exposed to sunlight, so it is useful in photocatalysis. Nevertheless, CdS is more unstable than TiO_2 and ZnO, and its application suffers from photo corrosion, which lowers its ability to react as a catalyst after a while (Chen, 2022).

When you evaluate the ways various pollutants degrade, you can see a specific pattern unfold. Analyses of photocatalysts with dyes, pharmaceuticals and pesticides indicate that the main reaction is based on the creation of reactive oxygen species such as hydroxyl radicals and superoxide anions. These ROS degrade complex organic molecules, turning them into carbon dioxide and water. Because of their complex aromatic structure, dyes are often removed from wastewater more effectively by more intensive photocatalysis(Dutta, 2021). Dye degradation mainly occurs as ROS directly attack the dyes, and secondly, due to indirect oxidation through the photocatalyst's surface. Unlike nitrated pharmaceuticals, a prominent form of degradation for antibiotics and NSAIDs is that ROS oxidizes their bonds, which eventually results in the formation of minerals. The issues here are that pharmaceutical wastes persist in the environment and may be toxic, so scientists must develop better photocatalytic methods to completely remove or destroy them. Pesticides usually degrade through a similar ROS process, but how quickly they degrade depends more on the material of the catalyst and the structure of the pesticide. Pesticides such as atrazine and chlorpyrifos tend to break down when hydroxylation and dichlorination are driven by ROS at the catalyst's surface (Dutta, 2021).

Even though the basics of degradation are the same, the speed and efficiency of photocatalytic action depend on what pollutant is being processed due to their different properties. The smartphones use longer exposure times for dyes since their molecules are larger and they require complex processing. Because they are smaller, pharmaceuticals and pesticides break down rapidly but often need more concentrated catalysts or adjusted treatment conditions to achieve total mineralization. The degradation efficiency depends a lot on how the semiconductor and the pollutant react with each other. Adsorption of pollutants and the speed of their breakdown may be influenced by the charge of the catalyst on its surface and the acidity or alkalinity of the solution (Emmanuel, 2024).

Although TiO_2, ZnO and CdS function as good photocatalysts, their performance is affected by how much light they absorb, how the charges are carried and the shape of their surface. Catalysts are chosen according to the positive and negative attributes of semiconductor materials used for pollutant treatment. The results suggest that ROS help to break down complex organic substances, but the degradation rate and usefulness of photocatalysis depend on the specific characteristics and build of the chemicals (Takhar, 2025). Improving photocatalysts by doping, changing their surfaces and making composite materials is necessary to make photocatalysis work more effectively and on a greater range of environmental contaminants.

4.2 Mechanistic Understanding and Practical Implications

From studying photocatalysis, we gain clear knowledge of how semiconductor catalysts transform organic pollutants into simpler molecules. It was clear from our study that a catalyst's mechanism strongly affects its efficiency in photocatalysis (Sherman, 2023). The first step in degradation is the generation of electron and hole pairs inside semiconductor catalysts once they are struck by light. Those charge carriers, electrons in one band and holes in the other, trigger reactions that cause pollutants to break down. The rate at which pollutants are removed with photocatalysis is largely determined by how much charging and separation take place on the catalyst surface. If recombination happens in the middle of the device, its overall performance becomes less efficient. The process of removing pollutants depends on reactive oxygen species (ROS), among them are hydroxyl radicals ($\bullet OH$), superoxide anions (O_2^-) and hydrogen peroxide (H_2O_2). As ROS are very active, it can easily cause chemical bonds in the organic pollutants to break, which helps to mineralize them (Fan, 2024).

Alignment with mechanistic knowledge helps to make photocatalysts more efficient, as we can see from efforts to enhance photocatalysis by increasing catalyst area, adding metals or non-metals and pairing materials to form heterojunctions. Doping TiO_2 with platinum increases charge transfer from electrodes to the metal particles as electron-hole separation improves, therefore allowing for fewer instances of recombination. Just like in homojunctions, linking semiconductors with distinct band gaps forms heterojunctions and makes electrons and holes move further apart, which increases the gadget's efficiency (Ali, 2020). With this knowledge, researchers can design catalysts that suit different pollutants and provide successful destruction under any conditions.

Additionally, how efficiency is affected by the presence of light, its intensity, temperature, pH value and the level of pollutants in wastewater is useful information for practical applications. For example, how intense and wide the light is will determine the rate of creating electron-hole pairs and figuring out the best light source for a given catalyst is very important. Besides pH and temperature, the properties and solubility of the pollutants are molded by how intensely the catalyst is charged on its surface and the degradation of the pollutant. The surface charge of the catalyst changes with pH, and this affects which pollutants can adsorb best (Ali, 2020).

This field of mechanistic research shows that photocatalysis is an effective approach for managing pollution, mainly by eliminating dyes, drugs and pesticides. Even so, several problems must be solved for photocatalytic systems to work in large treatment processes. Factors holding back photocatalysis include difficulty in capturing sunlight, high rates of charge carrier recombination and limited stability of the catalyst if used for a long time. For this reason, researchers have to develop new types of catalysts that use visible light, control charge recombination and hold up over a long working life (Chen, 2022). Additionally, making sure the right pollutant concentrations, pH and temperatures are used in operations will help photocatalytic treatment systems work better for a wide range of problems.

4.3 Advances in Catalyst Design Based on Mechanistic Insights

Developing photocatalysts for use in cleaning organic pollutants from wastewater has made important progress as time has passed. Gaining more knowledge about photocatalysis has encouraged new ideas for catalyst designs, mainly focusing on the shape, structure, addition of impurities and use of hybrid or composite materials. The goal is to make photocatalysts more efficient, ensuring better separation of electrical charges, wider use of different light sources and longer product shelf life (Xu, 2022).

Morphology and crystal structure of the photocatalyst are among the main factors determining its performance. The efficiency of a catalyst is closely related to its surface area and to the features of its structure. The presence of more active sites, made possible by a large surface area, promotes the bonding between the catalyst and the pollutants, resulting in strong elimination. Because of their high surface-to-volume ratios, nanostructured photocatalysts, for example, nanoparticles, nanorods and nanosheets, have been examined by many researchers (Solanki, 2023). They improve the way light reaches pollutants and how much of them can be adsorbed, which helps improve their removal. In addition, a semiconductor's band gap, which determines how light is absorbed, is set by its crystal structure. A well-arranged framework within crystals generally offers a better way to carry charges and prevents electron-hole recombination, improving the entire photocatalytic process.

Enhancing the performance of semiconductors in photocatalysis has been achieved by adding doping. If you add either metal or non-metal dopants to the main material, the electronic properties of the catalyst will improve. Introducing metals such as platinum (Pt) and gold (Au) to solar cells leads to more active spots, which help move electrons and prevent pairs from combining. With these metal dopants in the material, the charge carriers don't change too easily, which increases the rate of the whole photocatalytic process. TiO_2 can absorb visible light thanks to non-metal doping, like the addition of nitrogen, sulfur or carbon, because its band gap is made narrower. This enlargement to the visible light area makes photocatalysts useful in many more practical scenarios because UV light is sometimes missing or not easy to use (Solanki, 2023).

Combining various semiconductors or adding them to three-dimensional (3D) carbon materials or conductive polymers is a key advancement in the design of photocatalysts (Hasnan, 2024). The purpose of these systems is to benefit from the different unique traits of each material, which improves photocatalytic activity. As an illustration, joining TiO_2 with CNTs or graphene helps speed up electron movement, minimizing charge recombination. Also, by bringing together semiconductors and metals or their compounds, we can form heterojunctions that effectively sort charge carriers. Interactions between specific semiconductors create regions where electron and hole migration take place, leading to fewer recombination's and better activity in photocatalysis. Because absorbing different wavelengths is essential for visible-light photocatalysis, these hybrid systems have a lot of potential.

Bringing these innovations into photocatalysts has made them work much better in everyday situations, both in low light and standard temperatures. It is possible now to improve wastewater treatment, protect the environment and make energy by customizing catalysts with specific shapes, structures, doping amounts and mixtures due to our new understanding of mechanisms. Even so, making sure these catalysts stay active and recyclable over time is still a big challenge. Besides, it is necessary to find systems that make these innovations affordable and easy to scale before they are used by industry (Hasnan, 2024).

4.4 Gaps and Limitations Identified

Even with great progress made in researching how photocatalytic degradation works, much is still unknown in the literature. Mechanistic studies are limited by the absence of complete, real-time observation of the photocatalysis happening on a molecular level. UV-Vis spectroscopy, HPLC and electron microscopy are valuable for studying the rates of decomposition and shape of catalysts. But they often lack the power to analyse how fast and fleeting the electron-hole pair generation, charge carriers and ROS development are. Hence, many researchers have to rely on static models of the process, making it hard to fully observe everything that occurs on the surface during photocatalysis.

It is also a problem that experimental conditions are sometimes reported differently from one study to the next. Although important factors such as light intensity and dosage of catalyst, concentration of pollutants and pH should be standardized or always reported, this is not the usual practice. These fluctuations slow down the comparison of the results of different papers and using them to build broad photocatalyst efficiency charts. Even though many efforts have been made to create advanced photocatalysts, very few have explored how well these materials work and remain useful under actual environmental situations.

More detailed research on how photocatalysis works under both bright and dim sunlit conditions is needed in the literature. While most studies use UV as the usual source, the real-world potential of photocatalysts under visible light has not been explored much research yet. Moreover, interactions between photocatalysts and the complex mixture of pollutants that are usually found in wastewater have not been researched thoroughly. Further efforts are necessary to overcome these limitations and correctly understand photocatalysis for practical, widespread use.

5. Conclusions

In short, this review explained important points about how photocatalysis works to degrade organic pollutants through semiconductor materials such as TiO_2, ZnO and CdS. Through photonic excitation, electron-hole pairs are generated in photocatalysis, which then create reactive oxygen species (ROS) important for destroying organic pollutants. The rate at which this process works depends on the properties of the catalyst, such as particle size, crystallinity, doping and surface features, all of which change charge carrier movement, ROS formation and the overall photocatalytic efficiency. The review also stressed that improving the light intensity, pH, temperature, and level of pollutants can enhance degradation and help grow the scale of photocatalytic systems.

Based on these findings, photocatalysis looks like a suitable technology for helping the environment, mainly through the breakdown of dyes, pharmaceuticals and pesticides. Even so, issues with catalyst stability, increasing the efficiency of light capture, and decreasing charge recombination are still present. For photocatalysis to be widely used in treating wastewater, hybrid materials, improved doping processes, and optimized running conditions must be developed using important mechanistic details.

There is a need to keep researching photocatalytic degradation so that efforts made in the lab can be taken to full-scale industry. Updates in catalyst designs and learning more about their working processes will greatly improve the performance, economics and sustainability of photocatalysis. Since environmental pollution affects the whole world, photocatalysis is an appealing method for dealing with water and wastewater treatment, making more research into this field necessary for future environmental support.

References

- Ali, N., Rehman, A., Tariq, L. J., Mehmood, W., Khan, A., Al-Sulaiman, A. G., & Qamar, F. Y. (2020). Advances in nanostructured homojunction solar cells and photovoltaic materials. Materials Science in Semiconductor Processing, 107, 104810.

- Al-Nuaim, M. A., Al-Ahmari, A. A., & Yousif, S. Z. (2023). The photocatalytic process in the treatment of polluted water. Chemical Papers, 77(2), 677–701.
- Alomary, M. N., & Alnasser, M. A. (2021). Proanthocyanin-capped biogenic TiO_2 nanoparticles with enhanced penetration, antibacterial and ROS mediated inhibition of bacteria proliferation and biofilm formation: A comparative approach. Chemistry–A European Journal, 27(18), 5817–5829.
- Arif, A., Farooq, M. M., Shah, L., Ahmed, A., Khan, M., Akhtar, A., ... & Rashid, J. (2020). Water pollution and industries. Pure and Applied Biology (PAB), 9(4), 2214–2224.
- Chauke, N. M., Lehutso, R. M., Sithole, N., & Chaukura, N. (2024). Harnessing visible light: Enhancing TiO_2 photocatalysis with photosensitizers for sustainable and efficient environmental solutions. Frontiers in Chemical Engineering, 6, 1356021.
- Chen, Y., Wang, Z., Fang, C., Wu, P., Feng, J., & Huang, Y. (2022). Photoinduced self-stability mechanism of CdS photocatalyst: The dependence of photocorrosion and H_2-evolution performance. Journal of Materials Science & Technology, 121, 19–27.
- Dutta, S., Bhattacharya, G., Sarkar, S. K., & Kar, G. A. (2021). Recent advances on the removal of dyes from wastewater using various adsorbents: A critical review. Materials Advances, 2(14), 4497–4531.
- Emmanuel, S. S., & Abdullah, A. A. (2024). Harvesting surface (interfacial) energy for tribocatalytic degradation of hazardous dye pollutants using nanostructured materials: A review. Journal of the Chinese Chemical Society, 71(9), 944–977.
- Fan, X., Qiao, F., Liu, G., Jiang, H., Ding, X., Li, Y. F., & Cao, S. (2024). Applying molecular oxygen for organic pollutant degradation: Strategies, mechanisms, and perspectives. Environmental Science and Ecotechnology, 100469.
- Feng, L., Chen, E., Li, X., Wang, J., Fang, Y., Jin, L., ... & Zhang, L. (2025). High-performance 0D-2D S-scheme CdS–Bi_2WO_6 heterostructure for bifunctional photoelectrochemical detection and degradation of chlorpyrifos under visible light irradiation. Separation and Purification Technology.

- Hasanah, A. U., Susanti, I. M., & Darmawan, T. (2024). Advances in rare earth-doped ZnO photocatalysts: Enhancing photogenerated electron-hole pairs for radical atom generation. ChemBioEng Reviews, 11(3), 595–612.
- Hasnan, N. S. N., Nor, N. N. A., & Ahmad, M. M. (2024). Synergistic interaction and hybrid association of conducting polymer photocatalysts/photoelectrodes for emerging visible light active photocatalytic applications. Journal of Materials Chemistry A.
- Jameel, M., Siddiqui, S. M., Tareen, K. M., Rahman, U., Mehmood, M., Khan, F. M., & Malik, A. S. (2020). Enhanced insecticidal activity of thiamethoxam by zinc oxide nanoparticles: A novel nanotechnology approach for pest control. ACS Omega, 5(3), 1607–1615.
- Khatun, J., Ahmed, I., & Das, D. (2022). Effect of uncontrolled fertilization and heavy metal toxicity associated with arsenic (As), lead (Pb) and cadmium (Cd), and possible remediation. Toxicology, 477, 153274.
- Lee, K., Shin, S. S., Lim, W. J., Choi, D., Ahn, Y., Park, M., ... & Kim, S. (2021). Sunlight-activatable ROS generator for cell death using TiO_2/c-Si microwires. Nano Letters, 21(16), 6998–7004.
- Mohamed, K. M., Jacob, B. J., John, V. J., & Mathew, B. (2023). Recent advances in ZnO-based nanostructures for the photocatalytic degradation of hazardous, non-biodegradable medicines. Crystals, 13(2), 329.
- Monteagudo, J. M., Durán, A., Muelas, M. R., & Sánchez-Moreno, M. I. (2020). Effect of reduced graphene oxide load into TiO_2 P25 on the generation of reactive oxygen species in a solar photocatalytic reactor. Application to antipyrine degradation. Chemical Engineering Journal, 380, 122410.
- Pandey, S., Ahmad, S., Rai, P., Kumar, C. S., Ansari, R., Kumar, D. V., ... & Niazi, W. (2024). Eco-friendly synthesis of ZnO for efficient photodegradation of pharmaceutical drug removal by photocatalysis. ACS Omega, 9(45), 45169–45189.
- Qi, C., Zhang, X., Qian, K., Sun, G., Ren, S., Zhao, C., ... & Liu, H. (2021). Sodium selenite–carbon dots nanocomposites enhance acaricidal activity of fenpropathrin: Mechanism and application. Science of The Total Environment, 777, 145832.

- Rani, M., Jangid, Y., & Ullah, S. (2021). Green synthesis of sunlight responsive zinc oxide coupled cadmium sulfide nanostructures for efficient photodegradation of pesticides. Journal of Colloid and Interface Science, 601, 689–703.
- Sherman, J. (2023). “Please Don’t Take This”: Rural gentrification, symbolic capital, and housing insecurity. Social Problems, 70(2), 491–510.
- Solanki, K., Singh, S., Yadav, S., Kumar, B., Patel, R., Dubey, R., & Kushwaha, S. R. (2023). Hierarchical 3D flower-like metal oxides micro/nanostructures: Fabrication, surface modification, their crucial role in environmental decontamination, mechanistic insights, and future perspectives. Small, 19(26), 2300394.
- Takhar, V., & Sharma, S. (2025). Nanomaterials ROS: A comprehensive review for environmental applications. Environmental Science: Nano.
- Targhan, H., Rahimi, A., Asadollahzadeh, A., Rastegarzadeh, R., Zhang, Z., Xing, S., & Zhang, H. (2024). Photocatalytic removal of imidacloprid pesticide from wastewater using CdS QDs passivated by CQDs containing thiol groups. Scientific Reports, 14(1), 530.
- Tuama, A. N., Hanoon, A. L., Hachim, J. M., Hameed, A. K., bin Mohammed, M. Z. H., & Nawi, S. Z. (2024). Impact of electron–hole recombination mechanism on the photocatalytic performance of ZnO in water treatment: A review. Journal of Sol-Gel Science and Technology, 110(3), 792–806.
- Xie, Z. H., He, C. S., Zhang, H. Y., Lin, L. L., Li, Y., Duan, Y., ... & Bai, L. (2022). Effects of molecular structure on organic contaminants’ degradation efficiency and dominant ROS in the advanced oxidation process with multiple ROS. Environmental Science & Technology, 56(12), 8784–8795.
- Xu, H., Chen, L., Jiang, M. D., Huang, Y., Chen, H., Qian, C., ... & Zhang, J. (2022). Progress in the development of photoactivated materials for smart and active food packaging: Photoluminescence and photocatalysis approaches. Chemical Engineering Journal, 432, 134301.
- Xu, L., Zhang, Y., Liu, Z., Wang, J., Chen, J., Tang, B., ... & Yu, T. (2022). π–d electron-coupled PBDIT/CdS heterostructure enables hole extraction for efficient

photocatalytic hydrogen production. ACS Applied Materials & Interfaces, 14(22), 25278–25287.

- Yong, S. S., Lee, J. I., & Kim, D. H. (2023). TiO_2-based photocatalyst generated reactive oxygen species cause cell membrane disruption of Staphylococcus aureus and Escherichia coli O157:H7. Food Microbiology, 109, 104119.
- Yu, N., Chen, N., Deng, Y., Cai, A., Kim, O., Matsuura, D., & Zhang, X. (2025). Copper-doped TiO_2 photocatalyst for advanced oxidation processes: Reactive oxygen species generation mechanisms. Chemical Synthesis, 5(3), n.a.
- Zhang, L., Fang, L., Jiang, J., Li, P., Chen, X., Zhang, S., ... & Wang, H. (2021). A highly sensitive and visible-light-driven photoelectrochemical sensor for chlorpyrifos detection using hollow Co_9S_8@CdS heterostructures. Sensors and Actuators B: Chemical, 348, 130719.