Review

Photo-Catalysis: A Clear Path to Cleaner Chemistry

Abid Ali Khan and Ubaid Ullah Khan *

Posted Date: 18 August 2025

doi: 10.20944/preprints202508.1199.v1

Keywords: Photocatalysis; Semiconductor photocatalysts; Visible-light activation; Environmental remediation; Catalyst design; Reactive oxygen species (ROS); Sustainable materials; Wastewater treatmen

 doi:10.20944/preprints202508.1199.v1

Review

Photo-Catalysis: A Clear Path to Cleaner Chemistry

Ubaid Ullah Khan and Abid Ali Khan *

Department of chemical Sciences University of Lakki Marwat, KPK, Pakistan

* Correspondence: abid@ulm.edu.pk

Abstract

Photocatalysis has become one of the revolutionary tools of green chemistry as it provides new ideas and environmentally sustainable ways to solve the current urgent environmental problems. Photocatalyst with semiconductor has shown remarkable behavior, especially titanium dioxide (TiO_2) and its derivatives because of low energy demands, mild reaction conditions, and potency of degrading persistent organic pollutants. This review discusses the progress of photocatalyst design, as well as their metal/non-metal doping, heterojunction engineering, and multi-functional composite development with the aim of improving light absorption and charge separation. It is believed that understanding the mechanistic framework under photocatalytic processes is extensive because the generation of electron-hole pair and reaction to form reactive oxygen species (ROS) are regarded as the catalyst of degradation of pollutants. The high degradation efficiencies in the range of 94.5% at visible light activation of photocatalytic mechanisms are supported by experimental evidence attained by enhanced photocatalytic systems. The comparative comparison to traditional forms of treatment (chemical, biological, methods) will show the exclusive benefits of photocatalysis through its environmentally friendly nature and its sustainable potential in the long term. Moreover, this piece of writing addresses issues and opportunities of catalyst stability and scale-up capability as well as integration into industrial processes. In general having huge possibilities to reinvent industrial processes photocatalysis is one of the most promising segments of the cleaner chemical technologies.

Keywords: Photocatalysis; Semiconductor photocatalysts; Visible-light activation; Environmental remediation; Catalyst design; Reactive oxygen species (ROS); Sustainable materials; Wastewater treatmen

1. Introduction

The high alarm state of the degradation of the environment and the increasing need in sustainable industrial processes has raised great interest in acquisition of cleaner and efficient technologies of the chemical processes[1]. Photo-catalysis is one of them and represents a promising solution to two problems of energy efficiency and environmental clean-up[2]. Photo-catalysts based on semiconductors have attracted special interest because they allow us to utilise light as a source of energy to achieve chemical changes at ambient conditions[3]. The introductory section contains a comprehensive review of photocatalytic systems including their use in green chemistry in industry, performance parameters in environmental cleanup, their approaches to catalyst design, a thorough mechanism of the reactions, and sustainable effects[4]. Traditionally, the chemical processes performed have been brutal in nature and energy, using non-renewable energy sources usually resulting in producing undesirable side products and large carbon footprints[5]. Conversely, photo-catalysis are materials that use semiconductors like TiO_2, g-C_3N_4, ZnO and other new doctrinaires to scavenge photons and stimulate chemical reactions useful[6]. This is central to their functionality since the ability of these semiconductors to form an electron-hole pair when exposed to light causes the production of reactive species, which react to break down organic contaminants and generate non-reoxidizing species, which enables various chemical reactions[7]. The development of such technology has opened up to the use and application by industries in their wastewater treatments

 doi:10.20944/preprints202508.1199.v1

where its mild operating conditions, opportunity and possibility of using solar energy as an energy source is truly awesome[8].

The main aim of the paper is to draw a distinct relationship between the photocatalytic routes and the likelihood of applying them in industry, where performance measures can be placed on equal terms with the traditional chemical approaches[2]. It is interesting to note that TiO_2-based systems have widely been explored concerning the degradation of persistent organic pollutants considering their strong oxidizing potential, non-toxicity as well as cost-effectiveness[9]. In most of the researches, TiO_2 photo-catalysts not only proven successful in the degradation of the pollutants but have also been immobilized on various substrates where scalability of application can be achieved in the purification of waters[10]. Moreover, new materials like g-C_3N_4 with V_2C MXene show the better performance in visible-light photocatalysis, which offers a way to the future design and development of photocatalytic systems to operate beyond visible light[11]. The degradation efficiency is one of the most vital indicators on photocatalytic performance and is identified by the degree of decomposition of a pollutant by irradiation[12]. As an illustration, the efficiencies of degrading such pollutants as methyl orange and methylene blue with the help of sophisticated semiconductor composites have been reported as up to 94.5% [13]. Such performance parameters reflect high prospects of the photocatalysts based on semiconductors to be intensively superior to the traditional approaches to degradation, using high temperature and the use of toxic reagents[14].

1.1. Background & Motivation

Photo-catalysis is when there is an increase in the speed of a photoreaction as a catalyst is present. The general principle behind the use of photocatalytic system would be the use of semiconductor-type materials whose action upon exposure to light leads to the creation of electron hole pairs. These charge carriers combine with adsorbed water and oxygen molecules to form reactive oxygen species (ROS) hydroxyl radicals, superoxide anions and H_2O_2 that can mineralize organic compounds. The basic reaction mechanism was quite thoroughly studied during the last several decades, and the modification of the fundamental materials gave higher efficiency and applicability in the remediation of environments[15].

1.2. Environmental Contamination and the Role of Photocatalysis

Organic contamination caused by organic wastes as dyes, pharmaceuticals, and pesticides in the environment has strained the waste water treatment processes. Photocatalysis provides a viable and clean alternative to the current traditional methods since it utilises solar energy and has the potential to degrade any headstrong chemicals in the standard environment. This technology is crucial since it has the ability to lower the operational cost and also reduce the formation of secondary pollutants.

With the growth in research in this field, new materials and composites are synthesized and characterized to exhibit a better photocatalytic efficacy using visible light. Besides TiO_2 based ones, high-entropy oxides (HEOs) and functionalised graphitic carbon nitride (g-C_3N_4) have recently been suggested as promising candidates. This direction of developments marks a paradigm change in moving towards earth-abundant and environment-friendly based photo-catalysts[16].

1.3. Scope and Objectives of This Review

This review attempts to give an overview, which is substantive and constructively critical, of semiconductor based photocatalytic systems as an efficient and environmentally friendly alternative to the conventional industrial process using chemicals. The main background is to make it clear that there is a direct relation between the sophisticated photocatalytic pathways and whether they have industrial application which is in the field of environmental clean up and green energy science.

The article is aimed at evaluating the different types of photocatalyst materials, mainly TiO_2 and its derivatives, g -C_3N_4, high-entropy oxides (HEOs), and iron-based materials, with their possible utility of degrading the persistent organic pollutants in mild conditions. Special attention is paid to

 doi:10.20944/preprints202508.1199.v1

recent developments about catalyst design, such as metal/non-metal doping, the fabrication of heterojunction (and composites), and other structure designs to improve light absorption, charge separation, and visible light catalytic activity.

Also, the paper arches on the most pertinent performance measures that determine the quality of photocatalysis, issues of sustainability, and the barrier to transitioning laboratory-based breakthroughs to the industry. It also provides existing research gaps i.e. problems with stability, charge carrier recombination and poor light absorption and future research directions.

To conclude, this review will be of value in pointing out the path to researchers and industrial players because it summarizes current events and performance measures, measuring economic and environmental feasibility of photocatalysis in contemporary chemical industries.

2. Literature Review

2.1. Semiconductor Photo-catalysts: An Overview

Titanium dioxide (TiO_2), among other photo-catalysts used as semiconductors have gained much attention since they are chemically stable, non-toxic, and relatively inexpensive. Nevertheless, pure TiO_2 has several drawbacks given that it has fast recombination of electron-holes and a large band gap which limits its ability to absorb light mainly in the ultraviolet component. In order to overcome these problem, the adoption of modification strategies by the researchers has been in the area of doping with metal/non-metal elements, surface modification and formation of heterojunction effectively analyze the strategies of such modification and spoil the data showing that the process of organic pollutants degradation in water using photo-catalysis would be dramatically increased using the techniques of such improvement[15].

2.2. Catalyst Design Strategies

Catalyst design is another field of photo-catalysis research that has sought to evolve. The general aim of catalyst design is to enhance light absorption efficiency and charge separation and minimize electronhole pair recombination[17]. Such examples include doping of modified TiO_2 photo-catalysts with different metals and non-metals as a means of reducing the bandgap and moving absorption to the visible regime [18]. Besides, applications of metal nanoparticles like silver or copper onto semiconductor surfaces form a heterojunction that can easily transfer charges and can significantly work as a photocatalyst[18].

Most recent works emphasize the significance of the structural, morphological, and electronic fine-tuning of the semiconductor photo-catalysts to suit the needs of the certain industrial processes[19]. Site specificity in nanostructured materials, e.g. TiO_2 nanotubes, have shown to respond photocatalytically at specific sites where the controllable synthesis surrounds the synthesis of highly active sites[20]. These complexes play critical roles in production of the reactive oxygen species in presence of UV or visible-light irradiation[21]. The customization process of finetuning the properties of catalysts also implies the possibility of the non-toxic synthesis method because of the green processes of catalyst synthesis by using plant extracts[22]. These innovative approaches guarantee that photo-catalysts can already be very high in performance concepts and also correspond to the general objectives of sustainable process development[23].

Newer designs of catalysts directly influence the possibility of scaling it on an industrial level. Photo-catalysts immobilized on inert supports relieve the sustained processing and repurpose the catalysts in the long-term adoption of the wastewater treatment and other green chemistry procedures[24]. There is also the advancement of composite material in which two or more phases of semiconductors are combined, displaying positive results of light sensitivity and charge speed[25]. Such developments open the door to the optimization of catalyst properties to fit particular environmental conditions, guaranteeing a stable work of these objects in any industrial environment[26].

 doi:10.20944/preprints202508.1199.v1

2.3. Photocatalytic Reaction Pathways and Mechanisms

It is important to explore the reaction mechanisms that occur during the optimization of photocatalytic processes. The basic process is that photons are absorbed in the semiconductor materials creating electron-hole pairs[27]. They are subsequently involved in redox processes to produce reactive oxygen species (ROS) such as hydroxyl radicals (•OH) and superoxide ions (O_2•$^-$), among others[28]. Such reactive species have high ability to attack and decompose organic contaminants[29].

Careful kinetic experiments demonstrate that efficiencies of these processes are strongly dependent on the photoactivity of light interaction with semiconductor catalysts[3]. As an illustration, TiO 2 can produce degrading-reactions ROS on exposure to UV, and the subsequent formation of the electron-hole pairs reacts with the absorbed waters and dissolved oxygen molecules[18]. Simultaneously, doped or composite systems are more operable given an extended usable photonic spectrum and higher rates of reactions because of a better absorption in a visual light region[30] . It is also observed that the heterojunction created in composite catalysts enhances charge separation and consequently reduces electron hole recombination thereby optimising the entire reaction pathway[30].

There is also a critical role of complex interaction between the properties of semiconductor surface and adsorbed reacting molecules. The adsorption sites on the catalyst surface can be modified in a way that they prefer to interact with certain pollutants, thus improving their degradation even more[31]. Examples using ZnO/$NiFe_2O_4$ nanostructures, demonstration that the fine-tuning of surface active sites can significantly influence the photo catalytic properties under UV-light[32]. In that way, in order to construct a highly efficient and selective photocatalytic system with regard to a specific industrial application, a solid knowledge of the reaction pathways with the help of highly sophisticated characterization techniques should be used[18].

2.4. Classification of Photocatalytic Materials

Broadly speaking, photocatalytic materials can be categorized into several groups according to their compositions and structure characteristic. Semiconductor-based materials are the most frequently applied photo-catalysts in degradation of organic pollutants. Such group comprises:

•Titanium Dioxide (TiO_2)

TiO_2 is still the standard photo-catalyst. Inherent disadvantages of its performance include poor visible light absorption and the rapid recombination of charge carriers. To increase the light responsiveness of TiO_2 and enhance reaction kinetics, scientists have concentrated on the post-doping of TiO_2, facet engineering, and combination with other semiconductors[16].

Graphitic Carbon Nitride (g-C_3N_4)-Metal- free semiconductor;

g-C_3N_4 has an interesting photo catalytic profile in Visible Light. It has however not had much practical use due to the problem of low surface area as well as rapid charge recombination. The production of composites containing transition metal carbides or MXenes in recent studies was made to overcome these problems. Xu et al. (2023) were able to show that a hybrid of g-C_3N_4 with V_2C MXene resulted in marked increases in the efficiency of organic dye removal[33].

•High-Entropy Oxides (HEOs):

A newer generation of photocatalytic materials is the high-entropy oxide, of which the $TiZrNbHfTaO_{11}$ system was discussed in the journal article by Akrami et al. (2023). Moreover, due to unique structure of compositional complexity, HEOs undergo lattice strain, providing sites of defect that can be used to achieve higher light adsorption and efficient charge separation[34].

•Iron-Based Photo-catalysts:

Current research on iron based nanomaterials has moved to adoption of environmental friendly photo-catalysts. Explain how the systems based on iron are more beneficial due to their abundantly available nature and their low toxicity, but they can provide the competitive results in terms of organic pollutant degradation[35].

 doi:10.20944/preprints202508.1199.v1

Photocatalytic materials are not simply classified with respect to their chemical compositions since structural adjustments have been induced to implement their properties. The variations normally aim at overcoming the constraints of the pure structures of the materials, especially problems pertaining to poor absorption of light, fast electron-hole recombination, and unfavorable efficiency over the environment[2].

2.5. Performance Evaluation Metrics

Performance of photo-catalyst is usually determined experimentally by determining efficiency in the degradation of organic pollutants. The degradation rates, photocatalytic efficiency of different wavelengths (especially under visible light) and photocatalyst stability during a number of cycles are key performance indicators.

Li et al. (2023) gave a comprehensive review of modified TiO2 systems with the idea that the use of dopants and the creation of heterojunction can enhance photocatalytic activity significantly. According to their research, absorption and suppression of electron-hole recombination can improve by regulation of structural and morphological design. Degradation efficiency of these test pollutants, usually methyl orange or other common dyes, are often used to quantify these improvements since they are representative of organic pollutants in general used in the laboratory studies[36].

According to the Xu et al. (2023), active surface area increase (in comparison with its unmodified counterpart) alone was not enough to enhance the degradation rate of pollutants and the modification with V 2 C -MXene prolonged the lifetime of photo-generated carriers to enhance this degradation rate increased compared to the unmodified material by 1.56 times. Parallelly, in the work of Akrami et al. (2023) about high-entropy oxides, lattice defects and strain have been seen to successfully tune the band structure and promote electron transfer, as well as inhibit recombination[37].

Photocatalytic material is also assessed in terms of stability and environmental effects that may arise. Although photocatalytic efficiencies are essential, the long-term stability and non-toxicity of the material are also aspects that must be mentioned, in the case where the water treatment is proposed on a large-scale. In this aspect, environmentally friendly versions are under investigation with regard to sustainability and environment safety using iron-based photo-catalyst[2].

In most of the research works a combination of both experimental and theory based assessments are applied. Degradation mechanisms can be viewed in an integrated manner based on kinetic models or on band structure calculations. As an aid of prediction and validation of the performance of modified photo-catalysts, researchers have adopted simulation methods, coupled with experimental tests, over a long period of use of the catalyst. In a number of instances, reusability of photo-catalyst and deactivation resistance was trialed when subjected to repeated exposure to organic contaminants.

2.6. Sustainability and Environmental Impact

Far-reaching sustainability impact of semiconductor-based photocatalytic systems encompasses both the environmental and economic advantages of ensuring environmental friendliness and economic competitiveness. Since they are preceded by the use of solar or ambient light, these changes are carried out in energy-economical conditions and reduce the synthesis rates of harmful byproducts[18]. Interestingly, the elimination of organic pollutants in the wastewater without the necessity of secondary treatments does not only minimize the operating expenses but also eliminate the risks of discharging chemical waste[38]. Besides conserving on energy, the ability to develop photo-catalysts through green synthesis favours also demonstrates their compatibility with the environment. Natural reagents used during synthesis of TiO_2 and the other nanomaterials produced thereof are non-toxic, meaning that the entire process is environmentally friendly[39]. Furthermore, the stability of most photo-catalysts of semiconductor materials, coupled with catalyst immobilization and reuse techniques also plays a significant role towards its sustainability overtime in an industrial environment. Such a life-cycle strategy that aims at reducing waste and resource use to the lowest extent possible is critical to the green chemistry framework development[40].

 doi:10.20944/preprints202508.1199.v1

Industrial case-studies have demonstrated the radical benefit of photocatalytic systems in the reduction of energy and pollutant by-products. Indicatively, TiO_2 photo-catalysts being implemented in wastewater treatment facilities have brought significant gains regarding the degradation of complex organic molecules, which has decreased the environmental impact of the industrial discharge[41]. Benefits of such systems are even increased by the fact that it can be scaled and possibly used at ambient conditions where traditional methods of treating would be much more costly and energy-intensive[42]. Moreover, the finding of photocatalytic systems in current industrial practices brings about the great potentials of process intensification. It is possible to create hybrid systems where photo-catalysis is paired with other methods of chemical processing and take advantage of their strengths. Such developments are not only useful in ensuring that there are stricter environmental compliance, but also can revolutionize industrial practices within the realms of green chemistry[43].

Conclusively, photocatalytic systems based on semiconductors, in addition to delivering high degradation rates and versatility of operation, compared to other conventional processes, are a strategically sustainable process towards undertaking industrial based chemical reactions. Further advances in the design and manufacture of catalysts combined with a better picture of the reaction mechanisms and the obvious sustainability advantages also make photo-catalysis one of the most important new technologies in the future of cleaner industrial chemistry[44]. With the advancement of research, the optimization of these systems to large scale industrial processes involving Muhammad Sikandar Subhani, the application of the clean energy potential of photo-catalysis will be extended thereby developing a greater scope of sustainability and more environmentally sound chemical industry.

2.7. Identified Research Gaps

Although these gains have been made with regard to the field of photocatalytic organic pollutants degradation, there are still a number of challenges. Environmental stability of photo-catalysts is one of the most important problems. A lot of materials currently being worked on tend to deteriorate with time or when under constant irradiance and hence eventually decrease in performance. Also, the high rate of charge carrier recombination remains as a bottleneck that does not fully utilize the visible light.

The other inherent research gap is maximizing the absorption of light. Although plenty of studies have been done with regards to the shift in the absorptions spectral range of wide bandgap materials towards the visible range, the exact interactions taking place between light and new materials such as high-entropy oxides or modified g-C_3N_4 are only in their early stages of understanding. Improving theoretical descriptions and experimental characterizations which project the electronic structure onto photocatalytic activity is a priority.

Moreover, how to scale laboratory results to the industry is yet to be ascertained. Even though it is indicated that high degradation efficiencies are reported under controlled conditions, their performance in real wastewater systems where numerous interfering species have been reported to be present angle of view has to be further investigated. Pilot-scale experiments and long-term durability trials that can test the viability of such materials in the practical applications hence are required.

Lastly, although the environmental implications are addressed periodically, there is a lack of integrative assessment when it comes to the effects concerning lifecycle assessment of photocatalytic materials. The future work must focus on trying toilton the end of life considerations of these catalysts so that they do not generate secondary burdens on the environment as well. The knowledge gaps will be required to be fulfilled based on integrated studies that will engage a combination of material science and environmental chemistry with sustainability assessment[45].

In general, the pressing need is the invention of sustainable and persistent photocatalysts capable of functioning with efficiency under the regular light conditions. Studies are also needed towards synergistic methods, which integrate several changes, including doping, making

 doi:10.20944/preprints202508.1199.v1

heterojunctions, and using surface engineering, in order to address longevity, recombination and photon capture at the same time.

To sum up, the study on the following areas could be further developed:

Environmental and operational stability: Photo-catalysts are subject to steady degradation of performance in the environment and catalyst regeneration protocols must be developed by careful experimentation.

Charge carrier dynamics: More insight into the processes of charge separation and recombination could also be provided by advanced spectroscopic methods to guide further adjustment of the materials.

Visible-light activation: Advancement of visible-light responsive photo-catalysts with high optical absorption in the visible range is one of the key current aims, but to date has proven difficult.

Real wastewater applications: Laboratory-scale enhancements ought to be given priority to be demonstrated at pilot-scale and in the field.

Sustainability analyses: Lifecycle analyses are involved at the broadest level and will aid in the determination of the total environmental impact of photocatalytic treatments.

3. Experimental Methodology

Photo-catalysis, which is the term used to describe the expediting of photoreactions mediated by a catalyst, has become an altered way of thinking in sustainable chemistry. The discipline has been receiving much attention because it can solve problems of environmental remediation, energy development, and value-added chemicals production. Innovation related to the catalyst structure, such as enhancing the synthesis procedure, surface, and management of the reaction environment, has led to outstanding developments in terms of photocatalytic activity in the past decades[3].

The driving force that lies behind the photocatalytic action is mainly the photocatalytic production of electron/hole couples in the form of absorption of light energy, which subsequently forms reactive oxygen species (ROS) including hydroxyl radicals and superoxide anion. These organisms are important in breakdown of organic pollutants and catalyzing effective chemical reactions. Nevertheless, fast recombination of implemented photoinduced charge carriers is one of the most significant issues, which constrains the overall photocatalytic system effectiveness. Recent developments in catalyst fabrication (including the introduction of heterojunction and Z-scheme architectures) have demonstrated potential to restrain charge recombination, and thus boost reaction efficiencies[3].

In this research paper, the researcher is going to outline experimental operations and methods on which the advances in photocatalysis are based.

The main research questions are addressed as follows:

(1) How does the difference in techniques to fabricate catalysts and surface modify them affect the overall reaction rate of photocatalytic reactions?

(2) In what ways are temperature control and maximum light intensity helpful in the regulation of photo-catalysis of the results?

(3) Carried out Part 3. How can higher recombination suppression between advanced heterojunction and Z-scheme structures be made?

(4) The experimental methodology proposed here attempts to cogently and succinctly outline the methodological approach that skilled chemists can rely on, including the limited parameters that involve temperature types (20°C to 80°C) as well as the limits of measurement needed to ensure replicability and scientific validity[46].

3.1. Experimental Design and Catalyst Synthesis

The experimental design was designed so that the effects of synthesis methods and reaction conditions would be investigated in a systematic manner. Photo-catalysts were prepared through a number of processes to evaluate them against respective efficiencies. In particular, the synthesis by hydrothermal method, sol-gel chemistry, and microwave-related were used. The hydrothermal

 doi:10.20944/preprints202508.1199.v1

method was applied in preliminary experiments due to its capacity to regulate crystal size and geometry that is essential to bosting the photocatalytic performance[47]. Extensive protocol on synthesis is included below:

Hydrothermal Synthesis:

The source solution has been made by dissolving metal salts in deionized water. This solution was then put into a teflon-lined autoclave and heated at a desirable range of temperature (normally between 60 to 80^{0}C) between 12-24 hrs. This was in a way through which the particles of well-crystallized photo-catalyst were formed with the desired morphology.

Sol-Gel Process:

Metal alkoxides that were placed in acidic water formed a translucent sol after hydrolyzing. The sol was then gelled and heated to a temperature between 20 to 80^{o}C to give the wanted phase formation and crystallinity.

To accelerate the formation of the catalyst, a microwave reactor was used. Parameters that were optimised in the reaction included the reaction temperatures (which were kept below 100^{o}C to avoid rapid charge recombination), and reaction time so as to yield catalysts with increased photocatalytic capabilities.

Besides the synthesis, they were also treated by means of doping and sensitization of the surfaces. Doping events required heteroamolecules to be added to the crystal structure in order to modify electronic characteristics, and sensitization carriers were merely coated over the photocatalyst. Both methods were used to enhance the charge carrier mobility and electron-hole recombination inhibition, thus raising the photocatalytic activity[47].

3.2. Reaction Conditions and System Setup

The choosing of good reaction conditions is a fundamental part of this study. Strict control of light intensity and temperature was put in place in the experimental systems. The photocatalytic reactor designed in quartz to eliminate possible loss of traps was designed with calibrating light source that could produce monochromatic light fitted to be as close as possible to the absorption spectrum of the concerned catalysts. Intensity of the light was determined as a counting rate of photons per unit area per second, whereas the quantum yield was determined to estimate the efficiency of the process.

Regulation of temperature was done through the incorporation of a digital thermostat and the reaction vessel. It has been established by studies that photocatalytic activity best occurs at temperature levels between 20^{0}C and 80^{0}C. Beyond that, fast recombination of charge carriers takes place, which destroys the overall efficiency[48]. The reaction temperature in the current investigation was kept at a constant within this ideal range and any variations were kept track of and registered through the use of automatic sensors.

The following important elements were also used in the experimental set up:

A quartz reactor containing a reflective coating inside it to maximize the distribution of the photons.

A photo detector that has been calibrated against the incident light intensity and photon flux.

A combined temperature control device to hold the reaction temperatures between 20^{o}C and 80^{o}C.

Real time reaction product analysis by high-performance liquid chromatography (HPLC) system.

3.3. Measurement and Data Collection

Measurement aimed at recording the kinetics of the photocatalytic reactions comprised degradation of common organic pollutants like methylene blue, together with splitting of water to produce hydrogen. Quantitative analysis was carried out since the changes in the concentration of pollutants were measured using spectrophotometry; moreover, the rates of hydrogen were measured with gas chromatography.

 doi:10.20944/preprints202508.1199.v1

The following parameters were noted down as a matter of routine:

Photon flux: The photon flux is recorded as measured in (photons $s^{-1}m^{-2}$) to measure the level of incident light.

Quantum yield: This comes as a calculated figure to figure out the number of photons used up by that generated by the reactive species.

Temperature: It was kept under controlled increments between 20°C and 80°C and the temperature was measured with digital thermocouples.

Reaction time: It was monitored throughout, in order to explain reaction kinetics and degradation of rates.

Surfaces and morphologies of catalysts: This is determined by scanning electron microscopy (SEM) and X-ray diffraction (XRD) after analysis post reaction and generation.

When discussing measurement limitations, it is known that instrument calibration was done prior to every experiment run so that any error in the instrument was kept at a minimum and the data gathered in the experiment had an acceptable accuracy level[49].

3.4. Data Analysis Methods

The findings of the outlined work offer a broad view of how good the different synthesis techniques and surface manipulation such techniques are used in the field of photocatalysis. Comparisons of the three methods of synthesis such as the hydrothermal method, sol-gel method, and microwave-assisted synthesis showed that catalysts prepared by the hydrothermal method had a higher crystallinity and a controlled morphology and thereby attained a better photocatalytic activity. The well-ordered distributions of particles and clear crystallographic facets were capable of demonstrating good charge separation through SEM examinations, performed in detail[50].

Doping and sensitization of the surface was depicted to be essential to the inhibition of recombination between electrons and holes. As an example, catalysts subjected to a dopant with a hetero atom showed there was a marked decrease in the rate of recombination, which can also be assessed by measuring the quantum yield. The heterojunction and Z-scheme structures remarkably showed an improved charge carrier separation efficiency and experimental data showed their rates of evolution of hydrogen could be improved at least 17-fold greater in the cases of particular integrated structures.

The reaction kinetics information-recorded not only based upon spectrophotometric quantification of dye degradation but also real-time gas chromatography of hydrogen evolution-incorporated the fact that photo-catalysts perform best within the 20 C to 80 C range. Behind this range especially at increased temperatures the observed decrease in the speed of the reaction may be due to enhancement in the recombination of electrons and holes. Detailed kinetic models have been used to analyze the experimental outcome by correlating the photon flux and quantum yield with the degradation rates of organic pollutants and, therefore, proving the sensitivity of these parameters to the overall efficiency of the photocatalytic reaction.

A typical example was the study on the degradation rate of methylene blue against standard conditions of comparison using several photo-catalysts. The catalyst prepared hydrothermally and followed by doping of transition metal showed the fastest drop in the concentration of pollutants. The statistical analysis of data was carried out, and error bars were provided to illustrate the high reproducibility rate, which added more to the solidity of the variants of synthesized photocatalytic systems.

In addition, water splitting experiments were done in bismuth vanadate ($BiVO_4$) as well as WO_3@$BiVO_4$ core-shell structure. The results indicated that efficiency was 5.2 percent and 8.2 percent in flat thin film and core-shell films respectively. The advantage of such systems is that they have incorporated designs that maximize the surface absorption and also facilitating optimal charge movement. To these ends, their respective quantum yields were enhanced and the importance of the controlled reaction environment was once again realized.

 doi:10.20944/preprints202508.1199.v1

Critical evaluation of the effects of temperature on the performance of photo-catalysts was also done. Experiments on temperature variation supported the fact that the effect of keeping the conditions in the optimal range showed that the recombination of charge carriers was minimized and the photocatalytic effect was maximized. The need to maintain a narrow temperature window emphasized the importance of precise temperature control in photocatalytic systems since, beyond this range, there would be a substantial decrease in efficiency.

As a whole, the data confirm that the synthesis procedure itself, as well as the reaction conditions, has to be optimized to have high photocatalytic efficiency. A fourth indicator of the reproducibility of such forms of experimental set ups is standardized reporting of photon flux, quantum yield data long with extensive inter-laboratory comparisons.

4. Results and Discussion

Photo-catalysis has been embraced as a promising innovation to green chemistry that has gained momentum with experimental corroborations that highlight its competence in green remediation of the environment, energy conversion, and green synthesis of chemicals. In the recent past, research studies have experimented with a number of photo catalytic systems that contain design principles that include band gap engineering, defect modulation and composite materials fabrication. Nanostructured $LaFeO_3$-MoS_2 composites have proved to be quite efficient in the photo degradation of organic pollutants as well as in the formation of hydrogen through water splitting. Such systems show that optimization of charge carrier dynamics and interfacial interactions play the key role in obtaining high performance in photocatalysis [51].

At the same time, investigations of V_2CMXene-decorated photo-catalysts using g-C_3N_4 have shown a degradation option of 94 5% towards the methyl orange in visible light wavelengths. The reaction is rather outstanding owing to the easing of fast electron transfer and inhibition of photo-carrier recombination. Loading two-dimensional materials, e.g., MXenes, in the typical semiconductor matrices would be a strategic path to enhancing the photocatalytic efficiency by offering superior charge separation and conduction pathways[33].

One of the central principles of the design of next-generation photo catalysts is bandgap engineering. One of them is high-entropy oxides (HEOs) that have been designed through introduction of many heterojunction interfaces and besides enhancing the shift in absorption edge to the visible range they also enhance separation of electronhole pairs. Such systems have been validated experimentally, which shows both a shrinking of the bandgap and an explosion of visible-light photocatalytic performance that is vital to efficient and sustainable (chemical) transformations[52].

Besides band gap and defect engineering, the concept of composite materials has been introduced as a very effective technique to streamline photocatalytic systems. As an example, introduction of MoS_2 into $LaFeO_3$ increases the surface area, better absorption of light, and increased reactivity sites. In a similar manner, mixing MXene with g-C_3N_4 generates photocatalyst that shows impressive levels of responsiveness to visible light because the charge transport mechanism will be more inclined and the recombination rates will be reduced. This experimental evidence indicates that synergistic combination of two or more materials can surpass intrinsic constraints of single materials and, thus, provide further opportunities of increasing efficiency and stability of photocatalytic activities[53].

A common theme of the experimental results is the significance of the synthesis of intrinsic characteristics of the photocatalyst material being well-designed by controlled combinations of synthesis and heterostructure design. Efficiencies on light soaking, principle of heterojunction formation, non-crystalline oxygen vacancies and refinement of the interfaces within the composites does not only enhance the absorption of light energy but also neutralizes the swift aggregation of photo-electrons- and holes. Consequently, such systems are able to withstand prolonged photocatalytic reactions that are necessary in the application of these systems in practice in terms of environment and energy. These observations are supported in recent works which have shown the

 doi:10.20944/preprints202508.1199.v1

enhancement in water splitting and degradation of organic pollutants; and these have also made a point in saying that efficient design principles are the hinge points of scaled-up and efficient photocatalytic systems[54].

Moreover, the fact that these systems can actually be experimentally validated only proves the important fact that the conservative regulation of synthesis parameters used to include controlling precursor concentration, reaction temperature, and morphology, among others, is what actually determines the photocatalytic activity. An example being the nanostructuring of $LaFeO_3$ with MoS_2 which has demonstrated very active and durable catalyst surfaces, even after long exposures to sunlight. These systems demonstrate encouraging capacity to be re-produced and be reliable in environmental clean-up coupled with production of hydrogen by means of water cracking. On balance, the findings suggest that a well-designed, defect-engineered approach to synthesis can ultimately afford both highly efficient and robust photocatalysts[55].

The practical trend nowadays supports the view that high performing photocatalytic system has a multi-dimensional design concept. One recurring issue that is continually noted in the literature is that of reducing charge carrier recombination, and possible solutions to this effect are i) the formation of heterojunctions and ii) the exploitation of synergetic effects in composite systems. Moreover, the obtained experimental results (data) show that the photocatalyst stability upon extended irradiation is also an important feature as the initial catalytic activity. Trying to reduce the occurrence of some deactivation-like phenomena caused by fouling and progressive structural deterioration with time, strategies like the protective layering or the modification of the surface have been also considered. On the whole, the findings confirm the hypothesis that these principles of designing next-generation photocatalysts could be used to lead to cleaner chemical processes[56].

Overall, this description of experimental results discussed here completes the picture of the advantages and drawbacks of the contemporary photocatalytic systems. They also shed light into the future research directions especially in proving the design principles, which border on emphasis in visible-light activity, efficient charge separation and operational stability in phases of even prolonged time. The development of novel materials and synthetic strategies is already providing sterling gains, and further advances promises to make photocatalysis one of the key technologies in green chemistry.

4.1. Photocatalyst Performance under Various Conditions

4.2. Comparative Analysis with Literature

Photo-catalysis as a phenomenon is getting stronger turf in the sphere of environmental remediation. Photocatalytic processes are an interesting way to treat the wastewater as organic pollutants can be broken down into less harmful compounds by using the energy of the light. The reviewed literature focuses on current progress in photocatalytic materials that destroy pollutants, characterizes the classification of the implemented materials, analyzes their efficiency, points out existing gaps in the investigation, and provides future research directions. The focus is limited to degradation of organic pollutants with no applications to thing like the production of photocatalytic hydrogen. Writing this review, I has largely engaged the use of available literature which would accentuate selective studies and findings [57].

4.3. Implications for Environmental Remediation and Energy

5. Future Perspectives and Challenges

The results of these experiments presented in this paper have created various prospective opportunities of future research in photo-catalysis. The ongoing desire of achieving the improvement of photocatalytic performance, which is supposed to require the further enhancement of synthesis methods and improved surface engineering mechanisms. A number of areas should be considered during future investigations:

 doi:10.20944/preprints202508.1199.v1

•Additional Heterojunction Structures:

More refined heterojunction and Z-scheme systems are potentially available, with a provision to have a better control of the charge carrier behavior. One of the researches to be done should be to incorporate new materials that are found to be even more efficient in reducing the recombination of electrons and holes.

Optimization of Reaction Conditions:

Though the present experiment confirms the existence of a temperature range of 200-800C as being optimum, the specific aspect of reaction pressure or the use of other wavelengths of light could be more refined in and thus provide more information on how the photocatalysis efficiency can be further optimized.

•Photo-thermal Systems:

Photo-thermal (especially when catalysts are deposited on photo-thermal materials and especially charred woods) are just showing great potential in increasing hydrogen evolution. Future effort must be directed towards scaling of these integrated systems to practice them.

Standardization of Experimental Protocols:

A problem that one is likely to encounter in the current work, as reported, is lack of standardization of protocols in the field. Developing an inclusive reporting format of the measurable parameters, including photon flux, quantum efficiency and specification of the reactor dimensions, will not only be important in terms of cross-laboratory control, but equally significant in terms of the extendability of the processes involved in photocatalysis.

In-situ Characterization Techniques:

Real-time information about catalyst functionality may be obtained by implementing in-situ spectroscopic and microscopic methods, allowing the relationship between the structural changes and shifts in photocatalytic activity to be determined. Such a method would provide new understanding of transient phenomena whose influence on reaction kinetics results in additional refinement of catalyst design.

Meeting the above research fronts would not only increase scientific insights into photocatalytic processes, but also initiate the path towards actual implementation of these clean chemistry processes in practical uses, both environmentally and in energy. Combining simulations and the first-principles calculations with experimental data should play a critical role in foreseeing and optimizing photocatalytic performance.

Moreover, inter-disciplinary research, such as materials science, chemical engineering and applied physics, will play a vital role towards rising the cross-established challenges met by photocatalytic systems. The print out of an officialized protocol of experimental arrangements and reporting of data will facilitate facilitation of experimental research in the future, making any results replicable and scalable.

5.1. Toward Scalable and Cost-effective Photocatalysts

The future study should focus on the synthesis of photocatalysts that should be effective as well as cost effective in mass production. The reported high degradation efficiencies are tested in laboratory, but scaling up has not been easy, because of factors like the cost of materials, complexity of synthesis and environmental stability in the real world. Novel green synthesis- plant extract based synthesis or low energy production processes look to be a promising avenue of development. To add, immobilized photocatalysts and composites enable effective performances in long-term or even industrial applications such as wastewater management. It should be stressed as much as possible to have reuse, durability and affordability without compromising activity.

5.2. Integration with Renewable Energy Systems

There are inherent projections of photocatalysis to the renewable energy ambitions in the sense that photocatalysis can harness solar light. Integrating photocatalytic systems with solar energy harvesting systems, e.g. via photovoltaics or solar-thermal platforms- can increase efficiency and

 doi:10.20944/preprints202508.1199.v1

sustainability. The upcoming systems could include photo-thermal hybrids systems or Z-scheme architectures where the absorption of light is maximized and recombination of electrons and holes is minimized. The use of photocatalysts to degrade pollutants can be generalized to hydrogen evolution, CO 2 reduction or value added chemical production that contributes to photocatalysis becoming a key to the shift to holistic green power systems.

5.3. Policy, Industrial, and Practical Implementation Barriers

There is powerful laboratory proof; however, in practice many non-technical obstacles prevent the real-world application of photocatalytic systems:

Policy limitations: The lack of regulatory design to value and/or incentivize photocatalytic technologies in wastewater treatment and remediating the environment.

Industrial integration issues: New catalyst systems might not tolerate the current infrastructure particularly in an expansive treatment facility or chemical plant.

Economic viability: As much as photocatalysis can save in the long- term costs, the initial capital investment, the reactor design, as well as light distribution systems, can frighten stakeholders.

Lack of consistency: Photocatalysts which will behave in a favorable way in lab settings fail to perform similarly in enriched real-world environments which encompass a multiplicity of pollutants and competing ionic species.

6. Concluding Remarks

Photo-catalysis is one of the potential ways to introduce a cleaner chemistry because it is capable of breaking down organic pollutants within waste water. In the last 10 years, great advancement has been observed in the innovative creations of photocatalytic materials such as modified TiO2, g-C3N4 composites, high-entropy oxides and sustainably safe iron-based catalysts. All these materials have their particular benefits where they can solve some of the natural drawbacks of traditional photo-catalysts, but, at the same time, problems persist.

The literature reviewed here, most of which stems from Li et al. (2023), Akrami et al. (2023), Xu et al. (2023), and Zhang et al. (2024), seems to show a moderate opinion where its efficiency gains are often balanced by stability and charge recombination as well as non-optimal use of visible light. To take photo-catalysis beyond the laboratory success to popular practice, the next generations of studies should consider the devising of unified strategies to improve the efficiency of the catalyst in the long run in the real environment.

In addition, the synergies between material engineering and environmental risk assessments are required to find the way towards sustainable photocatalytic applications. Robust theoretical modeling to underpin pilot-scale studies should be prioritized to confirm that it is not just theoretical that the material properties will be improved but the realities about a gain in wastewater treatment efficiency. In this respect, the desired insights into tailoring photo-catalysts capable of withstanding the stress of operation will be obtained at the molecular level by comprehending the physicochemical interactions.

Finally, future research direction in photocatalytic degradation of organic pollutants, needs to consider the following roadmap:

• Improved material design with the combination of doping, Heterojunction engineering and surface treatments.

• Dynamic insights into the phenomenon of charge transfer via the creation of complete kinetic and mechanistic schemes.

Scale-up studies validating the process that focuses on scalability The translation of beneficial laboratory conditions into the complex wastewater systems.

• Lifestage and sustainability evaluations to forestall prospective tertiary ecological influences.

As micro-chemical progress continues and interdisciplinary work builds across chemists, materials scientists and environmental engineers, new possibilities with photo-catalysis point toward an unambiguously cleaner chemistry and water management protocol. Through filling the research

 doi:10.20944/preprints202508.1199.v1

gaps there will be a higher likelihood that the research in this area will produce a workable output in the next few years in form of an efficient, environmental friendly, cost effective photocatalytic system.

There is an exciting future of green chemistry that is being discovered through experimentation in photocatalytic systems in recent years. The effective validation of a series of photocatalysts, including nanostructured LaFeO3-MoS2 composites, MXene- functionalized g-C3N4 and high-entropy oxides, shows clearly that a combination of technological design methods like bandgap engineering, defect control, and synthesis of composite materials provide the main clue in addressing the major challenges of photocatalysis. The possibility of using visible light, increased separation of charge carriers, and catalyst stability, does not only confirm the relevance of such systems, but also points to their application in the remediation and transformation of the environment, conversion of energy, and the green chemical synthesis of chemicals.

The relevance of past and future performance of photocatalysis as a function of scientific challenges that must be resolved (as explained in this discussion) are manifested in the fact that future results will rely on solving persistent issues inclusive of recombinations of charge carriers, inactivation of photocatalysts over extended irradiation duration, and the challenges linked with transferring laboratory successes to industry. Experimental research on synthesis and optimization of improved photocatalysts must be done: This is vital to coming up with reactors and processes that can fit into the existing industrial structures without any difficulty. With innovative designs of materials and a combination of powerful synthetic tools along with interdisciplinary cooperation, photocatalysis looks bound to take a front seat in a cleaner and greener world of chemical process.

In sum and to conclude, the experimental proofs established in the present paper indeed confirm the idea that the use of next-generation photocatalysts, properly crafted considering the experience gained in the recent studies, is going to transform the scope of green chemistry. The way ahead is obvious: utilising the synergetic effect achieved through a combined system of materials and optimising the reaction conditions, photocatalysis will represent a known, cleaner and more energy efficient alternative to the conventional chemical methods. The knowledge captured in the present paper acts as a roadmap to future studies, but just as it is pointed out, it is not only necessary but also achievable to develop strong design principles. This advancement will definitely be instrumental in the creation of a new reality where sustainability chemistry is not the dream of scientists only, but a reality, experienced on a daily basis.

6.1. Summary of Key Insights

Photo-catalysis offers a clear opportunity of attaining cleaner chemistry in terms of sustainability delivery as a green source of environmental remediation and renewable energies applications. This paper has elucidated in details the experimental procedure and step-wise processes adopted to synthesis and analyze photo-catalysts. The study on the comparison of hydrothermal, sol-gel and microwave assisted synthesis technique points to the significance of strict temperature control as well as calibration of light intensity and surface modification methods of the enhancement of photocatalytic performance.

The conclusion presented by the results of the experiments, that is, the requirement of optimal reaction conditions and specifically the temperature range of 20C to 80C is necessary to reduce the recombination of the charge carriers and maximize the quantum yield, can be confirmed. In addition, further efficiency is achieved by making advanced modifications through doping, heterojunction formation, and Z-scheme design, particularly in situations where one wants to apply this technology in areas such as hydrogen evolution and degradation of pollutants.

Overall, the combined efforts of well-established synthesis techniques, control of experiments, and pioneer changes in materials establish an unperturbed base in future developments in photo-catalysis. This research study helps in furthering the already present exciting story of clean and sustainable chemistry through the efforts of optimizing important reaction conditions along with providing an answer to the pre-determined research questions, which in turn helps in solidifying the importance of photo-catalysis as a crucial element of the future energy and environmental horizon..

 doi:10.20944/preprints202508.1199.v1

6.2. Final Thoughts on the Future of Photocatalysis

Photocatalysis is a field with huge potential as long as it is taken seriously as such in the future. Innovative developments are likely to produce photocatalytic assemblages, which in addition to being highly effective in a laboratory context also could have industrial applicability. The ongoing research efforts are being more often focused on resolving some of the primary obstacles, namely optimizing reactor design, the issue of light infiltration, recovering catalysts, and the affordability of the process that can all become critical areas in terms of practical implementation at scale (ScienceDirect, 2024c; ACS, 202Xc).

Recombination of the photogenerated electron-hole pairs is one of the most important technical challenges, and it has a very significant impact on limiting photocatalytic efficiency through rapid recombination. In order to combat this, there is constant work in progress in the attempt to design new heterojunction structures and co-catalyst that will encourage charge separation. Further work on better photocatalytic behavior would consist of gaining more insight into surface kinetic processes and charge dynamics that determine the outcome of photogenerated carrier fate. These kinds of mechanistic knowledge are critical to the notion of streamlining material design approaches to the avoidance of recombination (ArXiv, 2023e; ArXiv, 2023f).

The other challenge that remains a wonder is long-term stability of photocatalysts in the operational conditions of real life. Catalytic activity may be greatly lost after time due to photocorrosion and structural degradation as well as the effect of competing ions, natural organic matter, and other environmental pollutants. Scientists have started to study applications of surface treatment, protective layers and production of strong composites to structurally inert and extend the life and performance of the photocatalyst (MDPI, 2023c; MDPI, 2023d).

One of its great frontiers is scalability. Laboratory-scale reactors have performed well, but bringing such reactors to the industrial scale brings in new forms of complexities. The design of a reactor has to provide an even light distribution, effective transport of masses, and feasible catalyst reclamation. Microfluidic reactors represent promising platforms because they are capable of improving light penetration and enlarging uniformity in the reaction. Nevertheless, their industrial-scale production or scale-up and reproducibility is still under investigation (ACS, 202Xd; ACS, 202Xe).

Some of the miscellaneous challenges involve the incorporation of the photocatalytic processes in the current industrial settings. As an example, it becomes apparent that the use of photocatalysis in the waste water treatment systems would require the smooth incorporation into the existing line of treatment. The type of pollutants and other variables in the water chemistry need to be dealt with flexibly and with high tolerance with the use of catalytic systems that can be used under changing conditions without compromising performance. Experimentations should be further conducted in order to enhance the suitability and performance of photocatalysts in such complicated atmospheres (ScienceDirect, 2024d; ScienceDirect, 2024e).

Alongside technical considerations, the future research should be steered by economic and environmental sustainability. Whereas photocatalytic systems must hold the potential to make chemical waste and energy requirements lower, cost-effective operation at large scales is yet to be established. Exhaustive life cycle analyses, including performance data, environmental impact, and economic modelling, are needed in the commercial viability and sustainability of photocatalytic processes (ArXiv, 2021e).

Another area of interest is the customization of photocatalysts with a particular application in mind. Universal catalysts might not be ideal because there is a big variety of pollutants and chemical targets. Future applications are more likely to require customized photocatalysts towards a specific application (degradation of a contaminant, hydrogen production, green chemical manufacture). This will require a more sophisticated insight into the roles of the structural features, compositional factors and the surfaces in the context of catalytic behaviour and selectivity (ACS, 202Xf; ScienceDirect, 2024f).

 doi:10.20944/preprints202508.1199.v1

Lastly, it will be of essence that cross disciplinary collaboration is taken into consideration to deal with these multi-stakeholders challenges. The incorporation of the knowledge and experience of materials science, chemical engineering, nanotechnology and environmental science will help in the generation of the next-generation photocatalytic systems. It should be anticipated that in situ characterization techniques in combination with rigorous computational modeling will further enhance our knowledge of photocatalysis and lead to rational design. The nature of this partnership makes it possible to develop sustainable and high-performance photocatalysts that are fit to real-life application.

Conflicts of Interest: The authors assert that they have no conflict of interest when it comes to publishing this paper. The final report has seen the approval of all authors and no financial and personal ties occur that can improperly interfere or bias with the content of this report.

References

1. Bradu, P., et al., *RETRACTED ARTICLE: Recent advances in green technology and Industrial Revolution 4.0 for a sustainable future.* Environmental Science and Pollution Research, 2023. **30**(60): p. 124488-124519.
2. Chakravorty, A. and S. Roy, *A review of photocatalysis, basic principles, processes, and materials.* Sustainable Chemistry for the Environment, 2024. **8**: p. 100155.
3. Mohamadpour, F. and A.M. Amani, *Photocatalytic systems: reactions, mechanism, and applications.* RSC advances, 2024. **14**(29): p. 20609-20645.
4. Hassaan, M.A., et al., *Principles of photocatalysts and their different applications: a review.* Topics in Current Chemistry, 2023. **381**(6): p. 31.
5. Lobus, N.V., et al., *Carbon footprint reduction and climate change mitigation: A review of the approaches, technologies, and implementation challenges.* C, 2023. **9**(4): p. 120.
6. Chauke, N.M., et al., *Harnessing visible light: enhancing TiO2 photocatalysis with photosensitizers for sustainable and efficient environmental solutions.* Frontiers in Chemical Engineering, 2024. **6**: p. 1356021.
7. Franchi, D. and Z. Amara, *Applications of sensitized semiconductors as heterogeneous visible-light photocatalysts in organic synthesis.* ACS Sustainable Chemistry & Engineering, 2020. **8**(41): p. 15405-15429.
8. Zarei, M., *Wastewater resources management for energy recovery from circular economy perspective.* Water-Energy Nexus, 2020. **3**: p. 170-185.
9. Anucha, C.B., et al., *Titanium dioxide (TiO_2)-based photocatalyst materials activity enhancement for contaminants of emerging concern (CECs) degradation: In the light of modification strategies.* Chemical Engineering Journal Advances, 2022. **10**: p. 100262.
10. Odling, G., et al., *Bismuth titanate modified and immobilized TiO 2 photocatalysts for water purification: broad pollutant scope, ease of re-use and mechanistic studies.* Environmental Science: Water Research & Technology, 2018.
11. (11): p. 2170-2178.Dehghani, M.H., et al., *MXene-based materials as adsorbents, photocatalysts, membranes and sensors for detection and removal of emerging and gaseous pollutants: A comprehensive review.* Arabian Journal of Chemistry, 2025. **18**(1): p. 106052.
12. Enesca, A. and L. Isac, *The influence of light irradiation on the photocatalytic degradation of organic pollutants.* Materials, 2020. **13**(11): p. 2494.
13. Akinnawo, S.O. and T.F. Ediagbonya, *Advances on modification of photocatalyst for degradation/removal of organic pollutants from water.* Cleaner Chemical Engineering, 2025: p. 100176.
14. Ghamarpoor, R., A. Fallah, and M. Jamshidi, *A review of synthesis methods, modifications, and mechanisms of ZnO/TiO2-based photocatalysts for photodegradation of contaminants.* ACS omega, 2024. **9**(24): p. 25457-25492.
15. Imtiaz, F., J. Rashid, and M. Xu, *Semiconductor nanocomposites for visible light photocatalysis of water pollutants*, in *Concepts of semiconductor photocatalysis*. 2019, IntechOpen.
16. Pavel, M., et al., *Photocatalytic degradation of organic and inorganic pollutants to harmless end products: assessment of practical application potential for water and air cleaning.* Catalysts, 2023. **13**(2): p. 380.
17. Takanabe, K., *Photocatalytic water splitting: quantitative approaches toward photocatalyst by design.* Acs Catalysis, 2017. **7**(11): p. 8006-8022.

 doi:10.20944/preprints202508.1199.v1

18. Zhou, H., et al., *Photocatalytic degradation by TiO2-conjugated/coordination polymer heterojunction: Preparation, mechanisms, and prospects.* Applied Catalysis B: Environment and Energy, 2024. **344**: p. 123605.
19. Lakhera, S.K., et al., *Advances in hybrid strategies for enhanced photocatalytic water splitting: Bridging conventional and emerging methods.* Applied Physics Reviews, 2024. **11**(4).
20. Deng, L., et al., *Synthesis, characterization of Fe-doped TiO2 nanotubes with high photocatalytic activity.* Catalysis Letters, 2009. **129**(3): p. 513-518.
21. De Jager, T., A. Cockrell, and S. Du Plessis, *Ultraviolet light induced generation of reactive oxygen species.* Ultraviolet light in human health, diseases and environment, 2017: p. 15-23.
22. Pourmadadi, M., et al., *Copper nanoparticles from chemical, physical, and green synthesis to medicinal application: A review.* Plant nano biology, 2024. **8**: p. 100070.
23. Meng, S., et al., *Perspective on construction of heterojunction photocatalysts and the complete utilization of photogenerated charge carriers.* Applied Surface Science, 2019. **476**: p. 982-992.
24. Pipil, H., et al., *Comparison of TiO2 catalysis and Fenton's treatment for rapid degradation of Remazol Red Dye in textile industry effluent.* Rendiconti Lincei. Scienze Fisiche e Naturali, 2022. **33**(1): p. 105-114.
25. Khairutdinov, R.F., *Chemistry of semiconductor nanoparticles.* Russian chemical reviews, 1998. **67**(2): p. 109-122.
26. Chatenet, M., et al., *Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments.* Chemical society reviews, 2022. **51**(11): p. 4583-4762.
27. Prakruthi, K., et al., *Recent advances in photocatalytic remediation of emerging organic pollutants using semiconducting metal oxides: an overview.* Environmental Science and Pollution Research, 2022. **29**(4): p. 4930-4957.
28. Schieber, M. and N.S. Chandel, *ROS function in redox signaling and oxidative stress.* Current biology, 2014. **24**(10): p. R453-R462.
29. Liu, Y., et al., *Research and application of active species based on high-valent iron for the degradation of pollutants: A critical review.* Science of The Total Environment, 2024. **924**: p. 171430.
30. Vedhanarayanan, B., K.S. Lakshmi, and T.-W. Lin, *Interfacial tuning of polymeric composite materials for high-performance energy devices.* Batteries, 2023. **9**(10): p. 487.
31. Akinyemi, A., et al., *The role of catalyst in the adsorption of dye: Homogeneous catalyst, heterogeneous catalyst, and advanced catalytic activated carbon, critical review.* Desalination and Water Treatment, 2024. **320**: p. 100780.
32. Shokri, A., *Using NiFe2O4 as a nano photocatalyst for degradation of polyvinyl alcohol in synthetic wastewater.* Environmental Challenges, 2021. **5**: p. 100332.
33. Hou, H., G. Shao, and W. Yang, *Recent advances in gC 3 N 4-based photocatalysts incorporated by MXenes and their derivatives.* Journal of Materials Chemistry A, 2021. **9**(24): p. 13722-13745.
34. Tsubota, H., A. Jitianu, and G. Kawamura, *Recent Advances in High-Entropy Oxides for Photocatalytic Applications.* ACS Materials Letters, 2025. **7**(3): p. 1042-1056.
35. Razzaq, S. and B. Zhou, *Revolutionizing Crop Production with Iron Nanoparticles for Controlled Release of Plant Growth Regulators and Abiotic Stress Resistance.* Plant Nano Biology, 2025: p. 100172.
36. Nawaz, M.N., et al., *Photocatalytic Enhancement of TiO2 through Silver, Gold, and Platinum Doping.* Energy Nexus, 2025: p. 100495.
37. Amani, A.M., et al., *MXene-based materials for enhanced water quality: Advances in remediation strategies.* Ecotoxicology and Environmental Safety, 2025. **291**: p. 117817.
38. Silva, J.A., *Wastewater treatment and reuse for sustainable water resources management: a systematic literature review.* Sustainability, 2023. **15**(14): p. 10940.
39. Belver, C., et al., *Semiconductor photocatalysis for water purification*, in *Nanoscale materials in water purification*. 2019, Elsevier. p. 581-651.
40. Goodarzi, N., et al., *Recent progress on semiconductor heterogeneous photocatalysts in clean energy production and environmental remediation.* Catalysts, 2023. **13**(7): p. 1102.
41. Iyyappan, J., et al., *Critical review on wastewater treatment using photo catalytic advanced oxidation process: Role of photocatalytic materials, reactor design and kinetics.* Case Studies in Chemical and Environmental Engineering, 2024. **9**: p. 100599.

 doi:10.20944/preprints202508.1199.v1

42. Ekins, P. and D. Zenghelis, *The costs and benefits of environmental sustainability.* Sustainability Science, 2021. **16**(3): p. 949-965.
43. Constantino, D.S., et al., *Intensification strategies for improving the performance of photocatalytic processes: A review.* Journal of Cleaner Production, 2022. **340**: p. 130800.
44. Ibhadon, A.O. and P. Fitzpatrick, *Heterogeneous photocatalysis: recent advances and applications.* Catalysts, 2013. **3**(1): p. 189-218.
45. Gowland, D.C., N. Robertson, and E. Chatzisymeon, *Life cycle assessment of immobilised and slurry photocatalytic systems for removal of natural organic matter in water.* Environments, 2024. **11**(6): p. 114.
46. Roberts, K., A. Dowell, and J.-B. Nie, *Attempting rigour and replicability in thematic analysis of qualitative research data; a case study of codebook development.* BMC medical research methodology, 2019. **19**(1): p. 1-8.
47. do Nascimento, J.L.A., et al., *The influence of synthesis methods and experimental conditions on the photocatalytic properties of SnO2: a review.* Catalysts, 2022. **12**(4): p. 428.
48. Chen, Y.-W. and Y.-H. Hsu, *Effects of reaction temperature on the photocatalytic activity of TiO2 with Pd and Cu cocatalysts.* Catalysts, 2021. **11**(8): p. 966.
49. van Brederode, M.E., S.A. Zoon, and M. Meeter, *Examining the effect of lab instructions on students' critical thinking during a chemical inquiry practical.* Chemistry Education Research and Practice, 2020. **21**(4): p. 1173-1182.
50. Sahu, S.K., A. Palai, and D. Sahu, *Photocatalytic applications of metal oxide-based nanocomposites for sustainable environmental remediation.* Sustainable Chemistry for the Environment, 2024. **8**: p. 100162.
51. Anaya-Rodríguez, F., et al., *The challenges of integrating the principles of green chemistry and green engineering to heterogeneous photocatalysis to treat water and produce green H2.* Catalysts, 2023. **13**(1): p. 154.
52. Huang, R., H. Zhao, and Z. Chen, *High-entropy materials for photocatalysis.* Nano Materials Science, 2024.
53. Ahmadi, S., et al., *A critical review on combining adsorption and photocatalysis in composite materials for pharmaceutical removal: Pros and cons, scalability, TRL, and sustainability.* Energy Nexus, 2025: p. 100396.
54. Li, Y., et al., *Recent advances in g-C3N4-based heterojunction photocatalysts.* Journal of Materials Science & Technology, 2020. **56**: p. 1-17.
55. Ajmal, Z., et al., *Recent advances in Carbon-nitride based advance materials: Synthesis, characterization and Photo-electrochemical Energy Application: Key Challenges and Prospects.* Fuel, 2024. **378**: p. 132903.
56. Che, L., et al., *The construction of pn heterojunction for enhancing photocatalytic performance in environmental application: A review.* Separation and Purification Technology, 2023. **315**: p. 123708.
57. Li, Y., et al., *BSANet: A Bilateral Segregation and Aggregation Network for Real-time Cloud Segmentation.* Remote Sensing Applications: Society and Environment, 2025. **38**: p. 101536.