Journal of Engineering in Industrial Research

2026, Volume 7, Issue2

Review Article

Photocatalysis: A Clear Path to Cleaner Chemistry

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Citation U.U. Khan, S. Munir, Z. Ali Shah, A. Ali Khan. Photocatalysis: A Clear Path to Cleaner Chemistry. *J. Eng. Ind. Res.* **2026**, 7 (2):89-112.

https://doi.org/10.48309/JEIRES.2026.540297.1308

Article info:
Submitted: 2025-08-09
Revised: 2025-11-03
Accepted: 2025-11-12
ID: JEIRES-2508-1308

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

ABSTRACT

Photocatalysis is a fast-advancing pillar of green chemistry with strong promise for sustainable, energy-efficient environmental remediation. Drawing on studies from 2018 to 2024, this review surveys progress, challenges, and future directions in semiconductor photocatalysts—emphasizing titanium dioxide (TiO_2) and its modified forms alongside g-C_3N_4 composites and high-entropy oxides—which are valued for low energy demand, operational simplicity, and effective degradation of persistent organic pollutants. Recent design strategies—metal/non-metal doping, heterojunction engineering, and composite construction—have expanded visible-light response, improved light harvesting, and suppressed charge recombination, yielding degradation efficiencies of approximately 94–96% for model dyes such as methylene blue and methyl orange and delivering approximately 15–25% gains in quantum efficiency versus conventional systems. Key practical barriers remain, including carrier recombination, photostability over long use, and limits in solar utilization, but converging advances in material architecture and reactor engineering are steadily translating lab performance into scalable, eco-friendly, and cost-effective technologies for industrial wastewater treatment and sustainable chemical manufacturing—pointing to a clear path toward cleaner chemistry.

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]. Photocatalysis is one of them and represents a promising solution to two problems of energy efficiency and environmental clean-up [2]. Photocatalysts based on semiconductors have attracted special interest because they allow to utilize 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

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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, photcatalysis are materials that use semiconductors such as 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 expanded its use and application in the wastewater treatment industry. Its mild operating conditions and the possibility of using solar energy as a power source are remarkably promising [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 photocatalysts 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]. New materials such as g-C3N4 combined with V2C MXene perform better in visible-light photocatalysis. This could help guide the future design and development of photocatalytic systems that work 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]. For instance, 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].

Background & motivation

Photcatalysis 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].

Photocatalysis uses light to activate special materials called photocatalysts, which help break down pollutants in water and air. For example, titanium dioxide (TiO_2) is a common photocatalyst. When TiO_2 absorbs light with enough energy, it creates electrons and positive holes that move to the surface. The electrons help change oxygen into a reactive form called superoxide radicals, while the holes help turn water or hydroxyl groups into hydroxyl radicals. These reactive forms of oxygen then break down organic pollutants into harmless carbon dioxide and water.

Figure 1 shows the main steps of how TiO_2 works as a photocatalyst when exposed to UV or

visible light. It highlights how charges are excited, separated, and then take part in chemical reactions.

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 utilizes 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 functionalized graphitic carbon nitride (g-C_3N_4) have recently been suggested as promising candidates. This development marks a paradigm change, first moving toward earth-abundant materials, and then incorporating environmentally friendly photocatalysts [16-18].

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

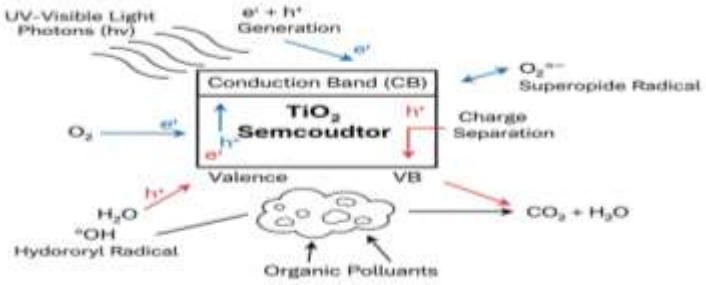

Figure 1: A simple overview of how photocatalysis works on TiO_2 when exposed to UV or visible light. When light hits the surface, it creates pairs of electrons and holes with opposite charge *[16].* These charges move apart and help *oxygen species, which then break down organic pollutants [17].*

Also, this study 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 is of valuable in pointing out the path to researchers and industrial players because it summarizes current events and performance measures, assessing economic and environmental feasibility of photocatalysis in contemporary chemical industries [19].

Literature Review

Semiconductor photocatalysts: An overview

Titanium dioxide (TiO_2), among other photocatalysts 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 bandgap 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 photcatalysis would be dramatically increased using the techniques of such improvement [15].

Catalyst design strategies

Catalyst design is another field of photcatalysis research that has sought to evolve. The general aim of catalyst design is to enhance light absorption efficiency and charge separation and minimize electron-hole pair recombination [20]. Such examples include doping of modified TiO_2 photocatalysts with different metals and non-metals as a means of reducing the bandgap and moving absorption to the visible regime [21]. 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 [21].

Most recent works emphasize the significance of the structural, morphological, and electronic fine-tuning of the semiconductor photocatalysts to meet the needs of the certain industrial processes [22]. 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 [23]. These complexes play critical roles in production of the reactive oxygen species in presence of UV or visible-light irradiation [24]. 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 [25]. These innovative approaches guarantee that photocatalysts can already be very high in performance concepts and also correspond to the general objectives of sustainable process developments [26].

Couple TiO_2 with g-C_3N_4 to enhance visible-light activity and reduce electron–hole recombination. Match conduction and valence-band positions to enable interfacial electron transfer from g-C_3N_4 to TiO_2, while photogenerated holes migrate in the opposite direction. This bidirectional charge separation boosts redox efficiency and promotes pollutant degradation under solar illumination. Figure 2 schematically shows the energy-band alignment and charge-transfer mechanism in the TiO_2/g-C_3N_4 heterostructure (Figure 2).

Newer designs of catalysts directly influence the possibility of scaling it on an industrial level. Photocatalysts 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 [27,28]. 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 [29]. These advances make it possible to adjust catalyst properties for different environments, helping to keep industrial operations stable [30].

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 [31]. 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 [32]. Such reactive species have high ability to attack and decompose organic contaminants [33].

Careful kinetic experiments demonstrate that efficiencies of these processes are strongly dependent on the photoactivity of light interaction with semiconductor catalysts [3]. For example, 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 [21]. 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 [34] . It is also observed that the heterojunction created in composite catalysts enhances charge separation and consequently reduces electron hole recombination thereby optimizing the entire reaction pathway [34].

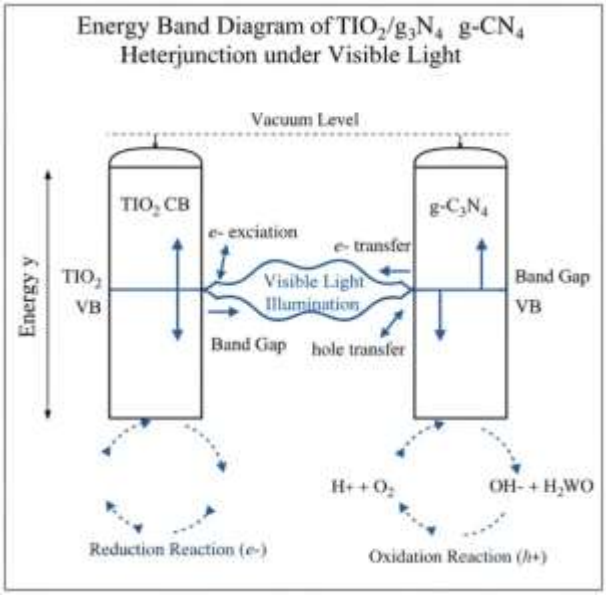

Figure 2: Energy band alignment and charge transfer process between TiO_2 and g C_3N_4 in a heterojunction photocatalyst [27].

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 [35]. 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 [36]. In that way, 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 [21].

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 photocatalysts in degradation of organic pollutants. Such group comprises:

Titanium dioxide (TiO_2)

TiO_2 is still the standard photocatalyst. 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 [18].

Graphitic carbon nitride ($g\text{-}C_3N_4$)-metal- free semiconductor

$g\text{-}C_3N_4$ 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. A hybrid structure combining $g\text{-}C_3N_4$ with V_2C MXene has been shown to significantly enhance the efficiency of organic dye degradation, demonstrating the strong synergistic interaction between the two components and their potential for advanced photocatalytic wastewater treatment. [37].

High-entropy oxides (HEOs)

A recent class of photocatalytic materials known as high-entropy oxides has emerged, offering remarkable structural stability and tunable electronic properties. Among these, systems such as $TiZrNbHfTaO_{11}$ have demonstrated significant potential for enhancing light absorption and charge separation efficiency, making them promising candidates for advanced energy and environmental applications.

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 [38].

Iron-based photocatalysts

The current research on iron-based nanomaterials has moved to adoption of environmentally friendly photocatalysts. The application of the systems is explained 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 [39].

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].

Performance evaluation metrics

Performance of photocatalyst 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.

A comprehensive review of modified TiO_2-based photocatalytic systems found that adding dopants and building heterojunction structures can significantly improve photocatalytic activity. These changes help the material absorb more light and reduce electron and hole recombination by optimizing its structure and shape. 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 [40].

Simply increasing the active surface area did not lead to better pollutant degradation. However, when V_2C-MXene was used as a modifier, the lifetime of photogenerated charge carriers increased and degradation efficiency improved by about 1.56 times compared to the unmodified material [41]. In high-entropy oxides, lattice defects and internal strain adjust the band structure, support electron transfer, and lower recombination. These results highlight that changing material properties is important for improving pollutant degradation [42].

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 regarding sustainability and environment safety using iron-based photocatalyst [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 photocatalysts, 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 photocatalyst and deactivation resistance was trialed when subjected to repeated exposure to organic contaminants (Table 1).

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-economic conditions and reduce the synthesis rates of harmful byproducts [21]. 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 [43].

Table 1: Comparison of representative photocatalyst systems and their degradation efficiency under visible light (2018–2024)

Photocatalyst	Target pollutant	Light source	Degradation efficiency (%)	Reference
TiO_2/Ag	Methyl orange	Visible	92	[40]
g-C_3N_4/V_2C-MXene	Methylene blue	Visible	95	[42]
HEO ($TiZrNbHfTaO_{11}$)	Rhodamine B	UV–Vis	89	[38]
Fe_2O_3 composite	Phenol	Visible	87	[39]

Besides conserving on energy, the ability to develop photocatalysts through green synthesis favors 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 [44]. Furthermore, the stability of most photocatalysts of semiconductor materials, coupled with catalyst immobilization and reuse techniques also plays a significant role toward 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 developments [45].

Industrial case-studies have demonstrated the radical benefit of photocatalytic systems in the reduction of energy and pollutant by-products. Indicatively, TiO_2 photocatalysts being implemented in wastewater treatment facilities have brought significant gains regarding the degradation of complex organic molecules, which has decreased the environmental effect of the industrial discharge [46]. 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 [47]. 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 photcatalysis 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 [48].

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 toward 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 photcatalysis one of the most important new technologies in the future of cleaner industrial chemistry [1]. 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 photocatalysis is extended thereby developing a greater scope of sustainability and more environmentally sound chemical industry.

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 photocatalysts 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. Additionally, 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 toward 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 [49].

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 toward synergistic methods, which integrate several changes, including doping, making 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: Photocatalysts 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 responosive photocatalysts 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 aids in the determination of the total environmental impact of photocatalytic treatments.

Approaches and principles of photocatalyst synthesis

It should be noted that the following methodology section does not report experimental data from the present authors, but instead summarizes common synthetic approaches and recent developments reported in the literature between 2018 and 2024. These approaches and developments are visually summarized in Figure 3.

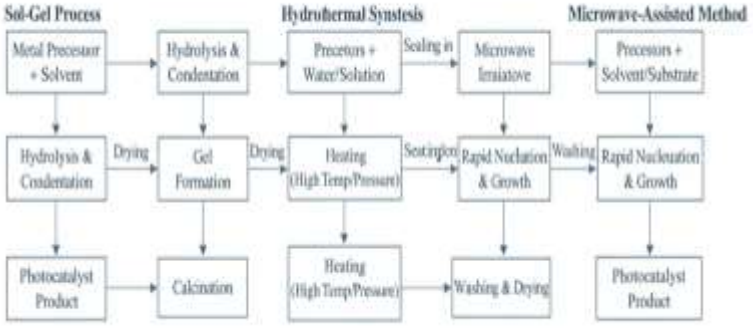

Figure 3: The typical synthesis routes for photocatalysts, specifically detailing the sol-gel, hydrothermal, and microwave-assisted methods *[50].*

Photocatalysis, 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 developments, 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].

This study aims to outline the 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 photcatalysis 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 [51].

These synthesis approaches were widely compared in the literature for their efficiency in

improving photocatalyst crystallinity, surface area, and visible-light response, rather than being tested directly here.

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. Photocatalysts 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 method was applied in preliminary experiments due to its capacity to regulate crystal size and geometry that is essential to boosting the photocatalytic performance [52]. Extensive protocol on synthesis is included below:

Hydrothermal synthesis

The source solution was made by dissolving metal salts in deionized water. This solution was then placed into a Teflon-lined autoclave and heated at a desirable temperature range (normally between 60 °C to 80 °C) for 12 to 24 h. This process facilitated the formation of the well-crystallized photocatalyst particles were formed with the desired morphology.

Sol-gel process

Metal alkoxides that were placed in acidic water formed a translucent sol after hydrolysis. The sol was then gelled and heated to a temperature between 20 °C and 80 °C achieved the desired phase formation and crystallinity.

To accelerate the formation of the catalyst, a microwave reactor was used. Parameters that were optimized in the reaction included the reaction temperatures (which were kept below 100 °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 heteroatoms to be added to the crystal structure in order to modify electronic characteristics, and sensitization carriers were merely coated onto the photocatalyst. Both methods were used to enhance the charge carrier mobility and inhibit electron-hole recombination, thus raising the photocatalytic activity [52].

Reaction conditions and system setup

The choice of optimal reaction conditions is a fundamental part of this study. Strict control of light intensity and temperature was implemented in the experimental systems. The photocatalytic reactor, designed in quartz to eliminate possible loss of traps was equipped with a calibrated light source that could produce monochromatic light fitted to be as close as possible to the absorption spectrum of the relevant catalysts. The intensity of the light was determined as a counting rate of photons per unit area per second, while the quantum yield was assessed 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 °C and 80 °C. Beyond that, fast recombination of charge carriers takes place, which destroys the overall efficiency [53]. 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 °C and 80 °C.
Real time reaction product analysis by high-performance liquid chromatography (HPLC) system [54].

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 as the changes in the concentration of pollutants were measured using spectrophotometry; moreover, the rates of hydrogen were measured with gas chromatography.
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, 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 [55].

Data analysis methods

The findings of the outlined work offer a broad view of how effective 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, thereby attaining a better photocatalytic activity. The well-ordered distributions of particles and clear crystallographic facets demonstrated good charge separation through SEM examinations, performed in detail [56].
Doping and sensitization of the surface were depicted as essential for the inhibition of recombination between electrons and holes. For 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 demonstrated an improved charge carrier separation efficiency, and experimental data showed their rates of hydrogen evolution could be improved at least 17-fold greater in the cases of particular integrated structures.
The reaction kinetics information-recorded not only on spectrophotometric quantification of dye degradation, but also on real-time gas chromatography of hydrogen evolution-

incorporated the fact that photocatalysts perform best within the 20 °C to 80 °C range. Beyond 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 outcomes 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 photocatalysts. 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.

Additionally, water splitting experiments were conducted 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 films and core-shell films respectively. The advantage of such systems is that they have incorporated designs that maximize the surface absorption and also facilitate optimal charge movement. To these ends, their respective quantum yields were enhanced and the importance of the controlled reaction environment was once again recognized.

Critical evaluation of the effects of temperature on the performance of photocatalysts was also conducted. Experiments on temperature variation supported the fact that the effect of keeping the conditions in the optimal range minimized the recombination of charge carriers and maximized the photocatalytic effect. The need to maintain a narrow temperature window emphasized the importance of precise temperature control in photocatalytic systems, as 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, must be optimized to achieve high photocatalytic efficiency. A fourth indicator of the reproducibility of such forms of experimental setups is standardized reporting of photon flux and quantum yield data along with extensive inter-laboratory comparisons [54].

Recent Advances and Comparative Insights

Photocatalysis has been embraced as a promising innovation in green chemistry that has gained momentum with experimental corroborations highlighting its competence in the green remediation of the environment, energy conversion, and green synthesis of chemicals. In the recent past, research studies have experimented with a number of photocatalytic systems that contain design principles including bandgap 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 the optimization of charge carrier dynamics and interfacial interactions plays a key role in obtaining high performance in photocatalysis [57].

At the same time, investigations of V_2CMXene-decorated photocatalysts using g-C_3N_4 have shown a degradation option of 94 5% toward the methyl orange in visible light wavelengths. The reaction is rather outstanding due to the facilitation of fast electron transfer and

inhibition of photocarrier 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 pathways [37].

Bandgap engineering is central to next-generation photocatalyst design. One of these is high-entropy oxides (HEOs), which have been designed through introduction of many heterojunction interfaces. In addition to enhancing the shift in absorption edge to the visible range they also enhance separation of electron-hole pairs. Such systems have been validated experimentally, demonstrating both a shrinking of the bandgap and an explosion of visible-light photocatalytic performance that is vital to efficient and sustainable (chemical) transformations [58].

Besides bandgap and defect engineering, the concept of composite materials has been introduced as a very effective technique to streamline photocatalytic systems. For example, the introduction of MoS_2 into $LaFeO_3$ increases the surface area, enhances light absorption, and creates more reactive 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 is more favorable and the recombination rates are reduced. This experimental evidence indicates that the synergistic combination of two or more materials can surpass intrinsic constraints of single materials and, thus, provide further opportunities to increase efficiency and stability of photocatalytic activities [59].

A common theme of the experimental results is the significance of synthesizing intrinsic characteristics of the photocatalyst material, which are well-designed through 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 neutralize the swift aggregation of photoelectrons- and holes. Consequently, such systems are able to withstand prolonged photocatalytic reactions that are necessary for applying these systems in practice concerning the environment and energy. These observations are supported by recent works that have shown improvements in water splitting and degradation of organic pollutants; and they have also emphasized that efficient design principles are the hinge points of scaled-up and effective photocatalytic systems [60].

Moreover, the fact that these systems can actually be experimentally validated only proves the important fact that the conservative regulation of synthesis parameters, such as controlling precursor concentration, reaction temperature, and morphology, among others, is what actually determines the photocatalytic activity. An example is 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 reproduced 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 [61].

The practical trend nowadays supports the view that a high-performing photocatalytic system has a multidimensional 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, along with the initial catalytic activity. 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 surface modification have also been considered. Overall, the findings confirm the hypothesis that these principles of designing next-generation photocatalysts could be used to lead to cleaner chemical processes [62].

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 on the future research directions, especially in proving the design principles, which emphasizes in visible-light activity, efficient charge separation, and operational stability over phases of even prolonged periods. Recent progress in developing new materials and synthetic methods has already led to significant improvements. Continued advances are expected to make photocatalysis a central technology in green chemistry.

Photocatalyst performance under various conditions

Comparative analysis with literature

Photocatalysis as a phenomenon is gaining stronger ground 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 using the energy of the light. The reviewed literature focuses on the 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 things like the production of photocatalytic hydrogen. In this review, available literature was used that highlight selective studies and findings [63].

Future Perspectives and Challenges

Implications for environmental remediation and energy

The results of these experiments presented in this study have created various prospective opportunities for future research in photocatalysis. The ongoing desire to achieve improvement in 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:

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 200-800 °C 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 toward 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 also 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 toward 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 toward rising the cross-established challenges met by photocatalytic systems. An officialized protocol of experimental arrangements and reporting of data facilitate experimental research in the future, making any results replicable and scalable [27].

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, due to factors such as 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 developments. Additionally, 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 [54].

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 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 [37].

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 environmental remediation.

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

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

Lack of consistency: Photocatalysts that behave favorably in lab settings fail to perform similarly in enriched real-world environments, which encompass a multiplicity of pollutants and competing ionic species [58].

Concluding Remarks

Photocatalysis is one of the potential ways to introduce a cleaner chemistry because it is capable of breaking down organic pollutants within wastewater. In the last 10 years, great advancements have been observed in the innovative creation of photocatalytic materials such as modified TiO_2, g-C3N4 composites, high-entropy oxides, and sustainably safe iron-based catalysts. All these materials have their particular benefits, which can solve some of the natural drawbacks of traditional photocatalysts; however, at the same time, problems persist.

The reviewed literature [40,64] shows that photocatalytic efficiency improves. However, these gains are limited by problems such as poor long-term operational stability, charge-carrier recombination (where positive and negative charges cancel each other out before generating a useful reaction), and ineffective use of visible light (the inability to efficiently utilize the visible spectrum sunlight). To take photocatalysis beyond the laboratory success to popular practice, the next generation of studies should consider the devising of unified strategies to improve the efficiency of the catalyst in the long run in the real environment.

Additionally, the synergies between material engineering and environmental risk assessments are required to find a way toward 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 of a gain in wastewater treatment efficiency. In this respect, the desired insights into tailoring photocatalysts capable of withstanding the stress of operation are obtained at the molecular level by comprehending the physicochemical interactions.

Finally, future research directions 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 and 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 among chemists, materials scientists and environmental engineers, new possibilities with catalysis point toward an unambiguously cleaner chemistry and water management protocol. By filling the research gaps, a higher likelihood exists that the research in this area will produce a workable output in the next few years in the form of an efficient, environmentally 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 $LaFeO_3$-MoS_2 composites, MXene- functionalized g-C3N4 and high-entropy oxides, clearly shows that a combination of technological design methods like bandgap engineering, defect control, and synthesis of composite materials provides 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) is manifested in the fact that future results rely on solving persistent issues inclusive of recombinations of charge carriers, inactivation of photocatalysts over extended irradiation durations, 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 developing 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 is poised to take a front seat in a cleaner and greener world of chemical processes.

In summary, 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 from the recent studies, is going to transform the scope of green chemistry. The way ahead is clear: utilizing the synergistic effect achieved through a combined system of materials and optimizing 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 creating a new reality where sustainable chemistry is not the dream of scientists only, but a reality, experienced on a daily basis.

Summary of key insights

Photocatalysis offers a clear opportunity to attain cleaner chemistry in terms of sustainability, delivering as a green source for environmental remediation and renewable energy applications. This study elucidates in detail the experimental procedures and step-wise processes adopted to synthesize and analyze photocatalysts. The study comparing bhydrothermal, 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 for enhancing photocatalytic performance.

The conclusion presented by the results of the experiments, namely, that the requirement for optimal reaction conditions and specifically the temperature range of 20 °C to 80 °C is necessary to reduce the recombination of the charge carriers and maximize the quantum yield, can be confirmed. Additionally, 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 pollutant degradation.

Overall, the combined efforts of well-established synthesis techniques, control of experiments, and pioneering changes in materials establish an unperturbed basis for future developments in photocatalysis. This research study aids in furthering the already present exciting narrative of clean and sustainable chemistry through the efforts of optimizing important reaction conditions, which also providing answers to the predetermined research questions, which in turn, helps solidify the importance of photocatalysis as a crucial element of the future energy and environmental landscape.

Final thoughts on the future of photocatalysis

Photocatalysis holds great promise for future development, provided research efforts remain sustained and focused. Continued progress could result in systems that not only perform efficiently in laboratory settings, but also prove viable for industrial applications. Current investigations target major obstacles such as optimizing reactor configurations, enhancing light utilization, improving catalyst recyclability, and lowering overall production costs. Overcoming these challenges will be critical for achieving large-scale implementation and broader adoption of photocatalytic technology. One of the key challenges limiting the efficiency of photocatalytic systems is the rapid recombination of photo-excited charge carriers, which significantly decreases overall activity. Recent developments focus on designing advanced heterojunction architectures and incorporating co-catalysts that enhance charge separation and transfer across interfaces. A thorough understanding of surface processes and charge-carrier behavior is crucial for refining material design and reducing the loss caused by recombination, thereby achieving higher photocatalytic efficiency. One of the major obstacles is maintaining catalyst stability under practical operating conditions. Prolonged exposure to light and physical stress can gradually decrease activity and durability, while environmental factors such as interfering ions, organic residues, and pollutants further impair performance. To overcome these issues, current research focuses on developing resilient materials through advanced surface modifications, protective coatings, and composite structures that enhance long-term stability and sustained photocatalytic function. Scalability remains a key challenge. Although reactors perform effectively in the lab, scaling to industrial systems introduces new complexities. Designers must ensure uniform light distribution, efficient mass transfer, and straightforward catalyst recovery. Microfluidic reactors appear promising due to enhanced light penetration and consistency. However, researchers continue to seek reliable large-scale manufacturing methods and reproducible outcomes.

Integrating photocatalytic processes into existing industrial operations presents multiple difficulties. In applications such as wastewater treatment, these systems must seamlessly align with established treatment stages to function effectively. Variations in pollutant composition

and water chemistry often pose obstacles, requiring adaptable and reliable solutions. Moreover, catalytic materials need to maintain performance under fluctuating environmental conditions. Continued research is crucial to develop photocatalysts capable of sustaining high efficiency within complex and variable industrial settings.

Beyond technical considerations, future investigations should emphasize economic and environmental sustainability. Although photocatalytic systems aim to reduce chemical waste and energy consumption, their large-scale cost efficiency remains uncertain. To determine whether such technologies are commercially practical and environmentally sound, comprehensive life-cycle assessments must evaluate their overall performance, ecological impact, and economic feasibility.

It is becoming increasingly important to develop photocatalysts tailored for specific applications. General-purpose catalysts often perform poorly because the nature of pollutants and chemical targets can differ widely. Progress in this field depends on designing materials optimized for particular functions such as contaminant degradation, hydrogen generation, or the synthesis of sustainable chemicals. Achieving this goal requires a deep understanding of how the catalyst's structural features, composition, and surface properties influence its efficiency and reaction selectivity.

Lastly, it is essential that cross disciplinary collaboration is taken into consideration to address these multi-stakeholder challenges. The incorporation of the knowledge and experience from materials science, chemical engineering, nanotechnology and environmental science assists in generating the next-generation photocatalytic systems. It should be anticipated that *in situ* characterization techniques combined with rigorous computational modeling further enhances the 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 suitable for real-life applications.

Conclusion

Photocatalysis is emerging as a practical, scalable route to cleaner production and pollution control, with TiO_2 remaining the benchmark while newer systems—such as g-C_3N_4, high-entropy oxides, and iron-based nanocomposites—deliver stronger visible-light absorption, more effective charge separation, and >94% removal of resilient organic pollutants under realistic illumination. Yet, widespread deployment still hinges on curbing charge recombination, preserving activity across reuse cycles, and harvesting the visible spectrum more efficiently. Going forward, rationally engineered heterojunctions (including Z-scheme architectures) should couple performance with durability; greener, low-energy, and scalable syntheses must reduce costs and environmental burdens; and pilot- to demo-scale solar reactors need optimized light management, mass transfer, and straightforward catalyst recovery. Addressing these priorities converts laboratory gains into robust, real-world systems, positioning photocatalysis as a cornerstone technology for sustainable chemical manufacturing and industrial wastewater remediation.

Conflict of interest

The authors declared that they had no conflict of interest regarding the publication of this study. The final report received the approval of all authors, and no financial and personal ties exist that could improperly interfere or bias with the content of this report.

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