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Photocatalysis for Wastewater Treatment: Green Chemistry Solutions

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Abstract
Water pollution due to various effluents from industries, pharmaceutical residues, dyes and pesticides and other uncharacterized pollutants is emerging as a serious environmental issue and requires sustainable and efficient wastewater treatment technologies. The use of conventional treatment methods may be limited due to high operation costs, chemical usage, secondary pollution, and lack of complete pollutant degradation. In such a scenario, photocatalysis has been found to be a potential green chemistry method for wastewater treatment using light-activated semiconductor materials. The research paper analyzes the potential use of photocatalytic technologies as environment-friendly solution for degradation of organic and inorganic pollutants in wastewater. Special attention is paid to the most recent developments of advanced photocatalytic materials such as titanium dioxide (TiO_2), zinc oxide (ZnO), graphitic carbon nitride (g-C_3N_4) and nanostructured composite catalysts, which can generate reactive oxygen species to break down complex pollutants into less harmful ones. The study also investigates the effect of the characteristics of the catalyst, the intensity of the light, the pH, the concentration of pollutants and the reaction conditions. It also emphasizes the role of solar energy, nanotechnology, and advanced oxidation processes in enhancing the efficiency of the treatment and minimizing the environmental impacts. In addition, the key implementation issues such as catalyst recovery, material stability, energy consumption, scaling of the treatment process and the presence of potentially harmful intermediate compounds are addressed. The study highlights the potential of integrating photocatalysis with green chemistry principles to improve the resource efficiency of wastewater management, safeguard the environment, and promote sustainable water re-use. It recommends that further research and development of photocatalytic materials and reactor design can enhance the feasibility implementation and help the shift towards cleaner and more sustainable water treatment systems.

Keywords: Photocatalysis, Wastewater Treatment, Green Chemistry, Advanced Oxidation Processes, Nanomaterials, Solar Energy, Environmental Sustainability, Water Purification.

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Introduction

The process of industrialisation, urbanisation and population growth has led to a significant rise in the generation of wastewater that has various organic and inorganic contaminants. Currently, worldwide, industrial effluents, agri-runoff, domestic sewage, pharmaceutical residues, dyes, heavy metals and emerging contaminants are the main pollutants in water. Untreated or under-treated wastewater that is discharged continuously into natural waters poses danger to aquatic life, pollutes the water, and poses health risks. Traditional methods of wastewater treatment, like physical separation, chemical coagulation, biological treatment, and membrane filtration, have made significant contributions to pollution control. They are frequently, however, limited by high operating costs, excessive consumption of chemicals, production of secondary sludge, lack of effectiveness in removing pollutants, and/or problems in removing persistent organic contaminants. The challenges have spurred scientists to seek environmentally friendly and technologically advanced alternatives to wastewater treatment.

The treatment of wastewater using photocatalysis has recently become an attractive method in the field of green

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chemistry, since it is capable of converting undesirable pollutants of the wastewater into more benign substances with the assistance of light energy. This process typically occurs, under appropriate light irradiation, when a semiconductor photocatalyst generates electron–hole pairs. These charge carriers engage in oxidation/reduction reactions and generate products of oxidation (hydroxyl radicals, superoxide radicals, and other highly reactive intermediates). Such species may attack complex organic compounds, be able to break down the molecular structure, and aid in their degradation to simpler substances, possibly carbon dioxide and water under appropriate reaction conditions. Photocatalytic treatment could also have the advantage of chemically degrading the contaminants which would reduce the environmental burden of wastewater disposal, as opposed to conventional treatment methods that can carry pollutants from one phase to another.

The design of efficient photocatalytic material is very important to enhance performance of wastewater treatment. The photocatalytic properties of semiconductor materials like titanium dioxide (TiO_2), zinc oxide (ZnO), tungsten trioxide (WO_3), graphitic carbon nitride (g-C_3N_4), and many metal-organic frameworks have been the focus of scientific research. Titanium dioxide is one of these materials that has been widely studied owing to its chemical stability, relatively low cost, non-toxicity, and high oxidation capacity. However, its potential use in wastewater treatment at large scale is limited by its wide band gap and the fact that it only uses a small portion of the visible spectrum of sunlight. To address these limitations, various material-engineering approaches have been studied such as metal doping, non-metal doping, heterojunction, surface modification, nano-structuring and composite photocatalysis. Such changes are intended to increase the absorption of visible light, to decrease the recombination of electron–holes, to increase the charge separation, and to increase the number of active reaction sites.

Photocatalysis can be used for the treatment of various types of contaminants in wastewater. Coloured organic compounds are emitted by the textile and dyeing industries and cause a decrease in light penetration in aquatic environments, and can also contain toxic and/or carcinogenic compounds. A new alternative method to overcome these dye molecules and reduce the amount of organic pollutants and colour by photocatalytic oxidation. Likewise, pharmaceutical and personal care products, pesticides, phenolic compounds, and other persistent organic pollutants pose serious problems due to their chemical stability and resistance to traditional biological treatment. Photocatalytic technologies present opportunities to remove these contaminants by creating reactive intermediates that are capable of breaking down complex chemical structures. The level of degradation and mineralization however, is affected by various factors such as the reactivity of the photocatalyst, light intensity, pollutant concentration, reaction time, solution pH and the presence of competing species.

Photocatalysis has several environmental benefits, from the green chemistry point of view. It is capable of using sunlight or other renewable light sources, which may help to decrease reliance on traditional energy-intensive treatment methods. It also offers the chance to reduce the amount of other chemical oxidants used and the amount of secondary chemical waste generated. For maximizing the efficiency of pollutant removal and overall treatment sustainability, the combination of photocatalytic systems with biological treatment, membrane technologies, adsorption processes and advanced oxidation processes can be used. This is especially pertinent in the context of decentralized wastewater treatment, water recycling in industries and sustainable water management infrastructure.

Although the practical implementation of photocatalytic wastewater treatment is still plagued with some scientific and technological issues, the technology has great potential. The efficiency of the system could be influenced by limited utilization of the visible light, fast recombination of the charge carriers generated by the light, aggregation of the catalysts, photo-corrosion, and recovery problems when the process is repeated. Moreover, the complex wastewater matrices with multiple pollutants, suspended solids and dissolved salts can

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interfere with the photocatalytic reactions. Another key factor is the disappearance of the original pollutant does not necessarily mean total detoxification. Thus, it is necessary to identify the degradation products of interest, measure total organic carbon reduction, toxicity assessment, and long-term catalyst stability to ensure environmental safety and effectiveness of photocatalytic systems.

The present research paper titled as "Photocatalysis for Wastewater Treatment: Green Chemistry Solutions" explores the scientific background, technological advances, and the environmental impact of photocatalytic treatment technologies. Semiconductor and Advanced Nanostructured Photocatalysts for Removal of Organic Pollutants and Emerging Contaminants from the Wastewater are the main topics. The paper also discusses the effect of various compositions of photocatalysts, light-induced reactions, working parameters and modification on the treatment efficiency. Special emphasis is placed on the combination of photocatalysis and green chemistry, on the use of renewable energy and on sustainable wastewater processing.

The study aims to emphasize the potential of photocatalytic technologies to play a role in the shift from traditional pollution control approaches to more sustainable and efficient wastewater treatment solutions that are environmentally friendly. The paper discusses the existing constraints and new research directions for scalable photocatalytic systems that can contribute to water quality protection, industrial sustainability and long-term environmental protection.

Background of the Study

Water pollution is one of the most significant environmental issues associated with the rapid industrialization, urbanization, population growth and increasing agricultural activities. Untreated or poorly treated wastewater discharge to rivers, lakes, groundwater systems and other natural water bodies has exacerbated water quality and disruption to aquatic systems. The environmental and public health impacts of industrial effluents contaminated by synthetic dyes, pharmaceutical residues, pesticides, heavy metals, organic solvents, etc. are of great concern. Pollution control has been significantly reduced by conventional wastewater treatment processes such as physical separation, chemical coagulation, adsorption and biological treatment. But certain methods may have restrictions in their applicability for complex, non-biodegradable, and emerging contaminants. Some processes merely transfer pollutants from water to another medium rather than completely eliminating their harmful effects. Efficient, sustainable and environmentally-friendly wastewater treatment technologies are consequently of growing importance.

Photocatalysis is an innovative treatment strategy for wastewater and has been the subject of much interest in this context. Advanced Oxidation Process (AOP) is a process which relies on light energy and semiconductor materials to catalyze chemical reactions that can break down organic contaminants in contaminated water. If the light energy is high enough, a suitable photocatalyst will absorb the light and cause an electron to be promoted from the valence band to the conduction band, creating electron – hole pairs. These charge carriers have a role in oxidation and reduction reactions, generating reactive oxygen species like hydroxyl radicals and superoxide radicals. They are highly reactive and are able to break down complex organic compounds into simpler ones, under certain reaction conditions causing complete mineralisation to carbon dioxide, water and inorganic ions. Such a process is of particular interest for wastewater treatment of persistent organic pollutants which are not easily removed by conventional methods, making photocatalysis a promising technique.

The possibilities of photocatalytic wastewater treatment by semiconductor based photocatalysts have been greatly expanded. The photocatalytic efficiency of materials such as titanium dioxide (TiO_2), zinc oxide (ZnO), tungsten trioxide (WO_3), graphitic carbon nitride (g-C_3N_4), and other metal-based composite materials has been studied. In these, titanium dioxide has been the focus of a lot of research due to its chemical stability, moderate cost, availability, and photocatalytic characteristics. However, some constraints, such as low visible-light

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absorption and photogenerated electron–hole pair recombination, may limit its applicability. Researchers have tried to tackle such problems by modifying the materials with metals and non-metals, by formation of semiconductor heterojunctions, surface functionalization, and by engineering the nanostructures. The former are employed to increase the absorption of light, the latter to promote charge separation and the third to make the degradation more efficient of the photocatalytic materials.

Photocatalysis becomes more relevant when it is analyzed from the green chemistry principles. Green chemistry is primarily about design of chemical processes and technologies that reduce use of hazardous substances, minimize waste generation, improve energy efficiency and promote environmentally sustainable practices. Photocatalytic treatment is also consistent with some of these principles, as it can benefit from using light as an energy source as well as have the potential to decrease reliance on traditional chemical oxidizing agents. In the photocatalytic systems, the use of solar energy provides another alternative to develop renewable energy based wastewater treatment system. Additionally, the use of re-usable photocatalysts and relatively mild operating conditions of treatment systems offer some potential for minimizing environmental impacts and operational costs. But the sustainability of photocatalytic treatment is dependent on the preparation of the catalyst, energy consumption, material recovery, and byproduct management.

Another key aspect of photocatalytic wastewater treatment is that of its use in various pollution intensive industries. Industrial activities such as the manufacture of textiles produce wastewater with synthetic dyes and chemical additives, and the pharmaceutical sector releases biologically active substances and drug residues into water bodies. Pesticides, herbicides and other chemical contaminants are added to water systems as a result of agricultural activity. Likewise, personal care products, detergents and emerging organic pollutants can be found in municipal wastewater. Photocatalytic processes may be useful in solving some of these contamination problems by initiating the degradation or transformation of contaminants that may not be amenable to traditional treatment. The enhanced overall treatment performance of these integrating biological treatment, membrane filtration, adsorption, and other advanced oxidation processes is a possibility.

Although all these benefits, photocatalytic wastewater treatment is still facing various scientific and technological hurdles in practical implementations. Many operating parameters such as light intensity, light wavelength, catalyst concentration, wastewater pH, pollutant concentration, reaction time, and interfering substances are important to consider for the efficiency of photocatalytic degradation. Limitations such as catalyst aggregation, insufficient light penetration, electron–hole recombination and separation/recovery of catalysts can also impact treatment efficiency. Furthermore, the fact that the original pollutant has been removed does not necessarily mean that all components of the pollutant have been removed, as intermediate components may be present in treated water. So, the efficiency of mineralization, identification of the degradation products, reduction of the toxicity of the degradation products and the reusability of the catalyst are the key factors for the determination of the environmental effectiveness of the photocatalytic systems.

Based on this background, the following study titled: “Photocatalysis for Wastewater Treatment: Green Chemistry Solutions” aims at the study of scientific principles, technological advancements, and environmental applications of photocatalytic processes in wastewater treatment. It aims to gain insight into the potential of advanced photocatalytic materials to play a role in the degradation of persistent pollutants and in the general goals of green chemistry and sustainable water management. The performance of semiconductor photocatalysts, the effect of operating conditions, the possible use of renewable solar energy and the difficulties with large-scale application are particularly emphasized. This research is intended to emphasize the photocatalysis as an effective sustainable treatment process and how this process can help in water pollution reduction, protection of aquatic environments, and improvement of sustainable wastewater management applications.

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Justification

Untreated and less treated industrial, agricultural, and domestic effluents are a current environmental concern due to their rising amount. Pollution with toxic chemicals, organic pollutants, dyes, pharmaceutical residues, heavy metals and emerging contaminants in water bodies can become serious threats to water bodies, public health and environmental sustainability. While these treatment methods are common, they are not always effective in removing all of the persistent pollutants from the wastewater, especially those that are chemically stable, non-biodegradable or present in low concentrations. All these challenges point out the need of wastewater treatment technologies that are innovative, efficient, and environmentally friendly.

In this context, photocatalysis has been shown to be a green chemistry technology suitable to purify wastewater. It makes use of light energy, especially solar radiation, with the help of proper semiconductor photocatalysts to trigger chemical reactions to break down harmful organic contaminants to less-toxic products, and in the appropriate conditions, mineralize them. Technologies based on engineered nanostructured photocatalysts (such as TiO_2, ZnO, g-C_3N_4), as well as new and advanced materials, hold tremendous promise in enhancing the efficiency of pollutant degradation and decreasing reliance on traditional chemical treatment processes.

The motivation behind this study is the increasing significance of finding economically viable, energy-efficient, environmentally friendly, and applicable solutions to wastewater treatment. The mechanisms of photocatalytic action, catalyst efficiency, light utilization, degradation rate and operating conditions can be investigated to gain insight into the effectiveness of this technology. Additionally, the recovery of the catalysts, stability of materials, secondary pollution problems, treatment costs, and scaling up are important issues to be understood for its industrial feasibility.

The study also has special relevance to green chemistry which focuses on pollution prevention, resource efficiency, minimisation of the use of chemicals and pollution responsible technological development. Understanding the solar photocatalytic processes could be a valuable way to develop a better way to treat wastewater in a cleaner manner as well as support water conservation, pollution reduction, and sustainable use of resources.

Hence, the research is justified because of the need to assess photocatalysis as a new and sustainable technology to replace or complement the conventional wastewater treatment technologies. Its objectives are to help to contribute scientific knowledge of photocatalytic materials and their environmental applications and to determine the opportunities and barriers for their practical use. The results can be beneficial to environmental researchers, chemical engineers, wastewater treatment sectors, policy makers, and sustainability practitioners seeking the improvement of water resources and lasting environmental protection.

Objectives of the Study

1. To investigate the basics of photocatalytic reactions used in the treatment of wastewater and the mechanisms of photocatalytic degradation of organic and inorganic pollutants, with particular attention to the role played by the light-activated catalysts.
2. To understand the different photocatalytic materials like Titanium dioxide (TiO_2), Zinc oxide (ZnO), Graphitic carbon nitride (g-C_3N_4) and advanced nanostructured catalysts for wastewater purification.
3. Asses the efficiency of photocatalytic reactions for the removal of dyes, pharmaceutical residues, pesticides, heavy metals and other emerging contaminants from the water.
4. To study the effect of operating conditions (light intensity, pH, catalyst concentration, reaction time and pollutant concentration) on the efficiency of photocatalytic treatment.
5. To evaluate and compare the advantages of photocatalysis for the environment and economy with the

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traditional wastewater technologies.

Literature Review

Conventional wastewater treatment systems have been facing a lot of troubles with the rise of persistent organic pollutants (POPs) like synthetic dyes, pharmaceutical residues, pesticides, and effluents from industrial sources that are discharged. The increased interest in photocatalysis as a treatment technique has been driven by the growing interest in the use of a light energy and appropriate semiconductor materials to catalyze chemical reactions that degrade harmful contaminants in an environmentally friendly manner. Photocatalytic processes are different from several conventional treatments, which result in a transfer of pollutants from one medium to another, since they can favor the transformation and, with proper conditions, mineralization of organic pollutants to simpler substances. The possibility of semiconductor photoelectrochemistry was first demonstrated by Fujishima and Honda (1972) who studied photoelectrochemical splitting of water using a TiO2 electrode. Their work provided an important scientific background for further advancements in light-driven reactions of chemistry and environmental photocatalysis.

Heterogeneous photocatalysis has had an impact on research on sustainable wastewater treatment. Hoffmann et al. (1995) reviewed the basics and the environment use of semiconductor photocatalysis, which describes the generation of an electron–hole pair under the influence of light and its participation in the oxidation–reduction reactions in the environment. These reactions generate ROS such as hydroxyl radicals and superoxide radicals that help to degrade organic pollutants. Likewise, Herrmann (1999) studied the basics and uses of heterogeneous photocatalysis and its use for environmental clean-up. Main focus of the study was on the catalyst properties, irradiation conditions and reaction environments that determined the efficiency of the treatments. These basic studies laid the groundwork for photocatalysis as a promising alternative method to clean water by using light to catalyze the chemical reactions required.

Titanium dioxide (TiO_2) has been the subject of much research due to its good chemical stability, low cost, photocatalytic property, and environmental friendliness. Fujishima et al (2008) talked about the progress of the photocatalysis for titanium dioxide and its application in environmental purification, self-cleaning surfaces and related technologies. Their work led to the understanding of the significance of the TiO_2-based materials in the development of eco-friendly treatment systems. Carp et al. (2004) reviewed the photo induced reactivity of titanium dioxide and discussed its usage in environmental purification. The effect of crystallinity, particle features and surface properties on photocatalytic activity was discussed. Notably, Chong et al. (2010) conducted a thorough review on the use of heterogeneous photocatalysis for water and wastewater treatment and highlighted the potential of TiO_2-based systems for the abatement of organic contaminants and the challenges faced in terms of efficiency, irradiation and feasibility.

Advanced semiconductor materials and nanostructured catalysts to enhance the photocatalytic activity have also been studied. Hoffmann et al. (1995) and Carp et al. (2004) found that the properties of semiconductors are important for the absorption of light and photocatalytic reaction. In this context, it was found that the synthesis, characterization and application of nanomaterials of TiO2 can be modified by changing their size to nanoscale, which affects the reactivity of their surfaces and influences their performance as nanomaterials (Chen and Mao 2007). Their results offer a foundation for designing photocatalysts having greater surface area and better ability to interact with substances in wastewater. Furthermore, Pelaez et al. (2012) analyzed the evolution of visible-light responsive titanium dioxide-based photocatalysts and highlighted the techniques of doping, sensitization and composite formation to address the shortcomings of the conventional UV active photocatalysts. The developments of course are particularly important for green chemistry as an enhanced

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utilization of visible light can boost the opportunity for solar wastewater treatment.

Photocatalysis has been widely used for the treatment of industrial wastewater, especially for the degradation of textile dyes and other synthetic organic compounds. Coloured effluents from textile industries often contain chemicals which are stable and may not be easily treated. Konstantinou and Albanis (2004) have investigated the photocatalytic degradation of azo dyes in aqueous solutions with the use of TiO2 and discussed the effect of operational conditions on the removal of pollutants. Their research proved that the photocatalytic oxidation process is important in tackling water pollution problems related to dyes. Likewise, Akpan and Hameed (2009) discussed the parameters that influence the photocatalytic degradation of dye by TiO_2 photocatalysts. They found that the catalytic use, initial concentration of pollutants, pH of solution and the intensity of the irradiation have significant effects on the degradation performance. The findings of these studies give scientific support to use the photocatalytic treatment in the textile and dye processing industries.

A second stream of research is focused on the elimination of pharmaceuticals, and emerging contaminants, from the waste stream. Some pharmaceutical and personal-care products and endocrine disrupting compounds may not be fully removed from wastewater by conventional wastewater treatment plants. These pollutants are capable of remaining in aquatic systems, which may lead to ecological issues. Chong et al. (2010) pointed out heterogeneous photocatalysis could be used to treat a variety of contaminants in water. Zambrano et al. (2022) also reviewed the photocatalytic removal of emerging contaminants from water and wastewater treatment, focusing on photocatalytic mechanisms, catalyst selection, and operational parameters. They pointed out that photocatalysis is an environment-friendly and promising method, but also noted the problems of catalyst recovery, fouling and the optimization of the process. These results highlight the potential of photocatalytic technologies for the design of future wastewater treatment systems that can remove pollutants that are hard to remove using traditional methods.

With the combining of nanotechnology and photocatalysis, there are more chances to enhance the efficiency of wastewater purification. The optical and surface properties of semiconductor nanoparticles are peculiar in such a way as to affect photocatalytic processes. In the article, Chen and Mao (2007) emphasized the significance of nanostructured TiO2 in the field of environmental and energy applications. Pelaez et al. (2012) also showed how composition and structure modifications of semiconductors can enhance their visible-light sensitivity. Recently, Hong et al. (2022) summarized the progress of semiconductor photocatalysts applied for wastewater treatment applications, highlighting the significance of bandgap engineering, heteroatom doping and heterojunction formation. They found that a more advanced semiconductor material could be used to break down dyes, pharmaceuticals and other hard-to-destroy chemicals. The utilization of such material design strategies is of special significance to achieve charge separation, minimizing electron–hole recombination and enhanced photocatalytic treatment efficiency.

Besides individual photocatalytic materials, researchers have looked at hybrid treatment systems with an integration of advanced oxidation processes and advanced wastewater purification processes with photocatalytic processes. These combinations may enhance contaminant removal and overcome some of the challenges presented by using individual treatment processes. The significance of the enhancement of semiconductor photocatalytic activity by material engineering and process development was discussed by Hong et al. (2022). Ahuja et al. (2023) summarized the latest development of photocatalytic materials and their application in wastewater treatment, including various photocatalytic materials, operation parameters and photocatalytic treatment of real industrial and domestic wastewater. Their study showed that it is essential to investigate the photocatalytic performance under conditions that represent wastewater treatment, and not just in laboratory environments with solutions of pollutants. In a similar way, new studies on photocatalytic coupling technologies have focused on the possibility of combining photocatalytic approach with other

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complementary treatment technologies in order to overcome the limitations of light use, catalyst recovery and reaction efficiency.

Photocatalytic wastewater treatment is emerging as an important step in the application of green chemistry in sustainable environmental technologies. Green Chemistry focuses on preventing pollution, minimizing chemical usage, optimizing energy use and designing safer chemical processes. The principles of green chemistry were laid out by Anastas and Warner (1998); these principles are used as a guide in the design of environmentally friendly chemical technologies. In this regard, photocatalysis has also several potential advantages: it is possible to use light as an energy source and to diminish the use of some of the chemical oxidants. The environmental effects, however, rely on the methods used to prepare the catalysts, the toxicity of the catalysts, the amount of energy consumed, and the treatment of the reaction by-products. Photocatalytic materials with higher efficiency and greater application in actual wastewater must be developed, which was noted by Hong et al. (2022). So the assessment of photocatalysis on the basis of green chemistry principles should not only focus on the pollutant degradation efficiency, but also consider the overall environmental impact.

In recent years, an increasing number of investigations have been conducted on the photocatalytic process driven by solar energy as an alternative energy intensive process. Photocatalytic systems can be potentially more environmentally friendly, and require less external energy input, when using natural sunlight. The use of various photocatalytic materials for wastewater treatment was studied by Ahuja et al. (2023) and their efficiency in different operational conditions. In a study published in 2024, Jabbar et al. delved into the advancements in semiconductor photocatalysis systems, focusing on heterojunctions engineering, charge transfer mechanisms, and environmental contaminant degradation. The results they found suggest that the design of semiconductors could be refined to increase photocatalytic activity and to make better wastewater cleaning systems. Furthermore, recent research on the photocatalytic purification of water using solar energy has highlighted the significance of reactor design, light distribution, and the characteristics of the photocatalyst on the scale-up to practical water purification systems.

Scalability and commercialization of photocatalytic wastewater treatment is still a research issue. While laboratory studies often show very good results of pollutant degradation, industry demands efficient reactor configurations, continuous operations, catalyst stability, and effective pollutant treatment processes that are affordable. Ferreira et al. (2025) summarized the developments of a heterogeneous solar photocatalytic reactor for wastewater treatment, discussing the reactor designs, operating principles, and pilot- and industrial-scale implementation problems. They identify the importance of studying reactor engineering in addition to the development of photocatalysts. Additionally, Rajanikara Swamy et al. (2026) reviewed the recent developments in the field of photocatalytic wastewater treatment, highlighting the advancements in the development of nanomaterials, degradation of pollutants, and the associated challenges regarding the production costs, scalability, and industrial feasibility. These studies indicate that further study should combine material innovation, process engineering and environmental performance evaluation.

In overall, the available literature shows that photocatalysis has a great potential as a green chemistry solution for wastewater treatments. Its scientific basis has already been established in previous studies, and its efficiency with semiconductor materials has been proven in previous studies, as well as uses with dyes, pharmaceuticals and other persistent contaminants. It has been expanded by recent advancements in nanotechnology, visible-light responsive catalysts, heterojunction materials, and reactors powered by sunlight. However, issues with catalyst recovery, material stability, energy requirements, reaction by-products, and on a large scale implementation are not yet solved. The present research is therefore aimed at investigating photocatalysis as a sustainable technology for wastewater treatment, with a specific interest on the principles of green chemistry,

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the development of advanced photocatalytic materials, the efficiency of pollutants degradation and the feasibility of environmental friendly wastewater treatment technologies.

Results and Discussion

This work underlines the important potential of photocatalysis as an environmental friendly technology for wastewater treatment. The results have shown that photocatalytic processes have proven to be very effective in the degradation of various organic pollutants such as dyes, pharmaceutical residues, pesticides or other persistent chemical pollutants found in wastewater. Semiconductor photocatalysts react with an appropriate light source to produce reactive oxygen species, mainly hydroxyl radicals and superoxide radicals, which break down the more complex organic compounds into simpler ones. Modifications of the pollutant degradation efficiency using semiconductor nanocomposites, e.g., titanium dioxide (TiO_2), zinc oxide (ZnO), graphitic carbon nitride (g-C_3N_4), and other nanocomposites have shown significant potential. The results indicate photocatalysis as an alternative or a complementary method for wastewater treatment compared to the traditional methods.

The results also show that properties of photocatalysts, such as physical and chemical properties, play important roles in determining the photocatalytic efficiency. The particle size, crystallinity, surface morphology, surface area and band-gap energy are all important parameters for understanding the overall degradation performance. Nanostructured photocatalysts typically have a larger active surface area and therefore interact more with pollutant molecules, which results in increased surface activity. Of particular interest are the changes that can be made to TiO_2 and ZnO using appropriate metals, non-metals or carbon-based materials to promote greater light absorption and less loss through electron-hole recombination. These changes are crucial for enhancing the photocatalytic performance under visible light and reducing the reliance on ultraviolet light. Thus, the focus of the discussion is on the development of advanced photocatalytic materials that are able to function efficiently under natural sunlight.

Another significant result is related to treatment of effluents from industrial dyeing which are contaminated with synthetic dyes and toxic organic compounds. Conventional treatment processes may require substantial chemical inputs and may not completely eliminate certain persistent pollutants. The mechanism of progressive degradation of the complex organic molecules is possible, however, through photocatalytic oxidation. The reduction of colour intensity, chemical oxygen demand (COD), and total organic carbon (TOC) as a result of the process depends on the catalyst, the type of irradiation, the concentration of the pollutant, and the duration of treatment. But when the original pollutant is gone, the mineralisation is not necessarily complete. Intermediate compounds can end up in treated water, so further chemical or ecological toxicity testing and mineralization testing might be necessary before using the process for environmental release.

In addition, photocatalysis has been applied to pharmaceutical and healthcare wastes and shows great environmental relevance. Personal-care product contaminants, pharmaceutical residues, and antibiotic residues are possible contaminants in aquatic environments from domestic sewage and healthcare facilities. Due to their chemical stability and biological activity some of these substances are hard to remove by normal biological treatment methods. Such contaminants can be oxidized and transformed with the use of reactive species formed in the photocatalytic treatment. This is especially relevant for the degradation of antibiotic compounds as the persistence of these compounds in aquatic systems could play a role in the emergence and transmission of antimicrobial resistance. However, the conditions for photocatalytic treatment should be optimized with great care to reduce the generation of potential transformation products that may be harmful.

The study also pinpoints the effect of operating parameters on the performance of the wastewater treatment

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system. Photocatalytic reactions are sensitive to the light intensity, irradiation time, pH, catalyst dose, initial pollutant concentration and the presence of dissolved oxygen. Higher catalyst amount could result in higher pollutant degradation initially due to higher number of active sites. High concentration of the catalyst, however, can facilitate light scattering and reduce the light penetration making the process less efficient. Likewise, the surface charge of the catalyst can be affected by the pH of the wastewater, as can be its adsorption behaviour of pollutants. Increased concentrations of pollutants can also cause lower degradation efficiency due to competition for active sites and decreased light transmittance through the wastewater medium. Thus, it is essential to optimize the operating conditions to ensure effective treatment with energy and material efficiency.

The green chemistry potential of photocatalysis has a number of benefits over methods that rely much on chemical oxidants. The application of sunlight to provide energy will help to reduce electricity demand, and the use of reusable photocatalysts can help reduce the amount of materials used and secondary waste generated. The technology also presents opportunities for connecting up wastewater treatment with renewable energy systems and decentralised wastewater treatment facilities. By binding photocatalysts to appropriate support materials, the photocatalysts can be easily recovered and reused, thus decreasing the possibility of nanoparticles being released into treated water. These methods are especially applicable in industries which want to enhance their environmental performance, decrease the use of chemicals and increase their use of cleaner production.

Although these benefits exist, there are a number of technological challenges that need to be addressed on a large scale for photocatalytic wastewater treatment. The low visible light (VL) sensitivity of conventional semiconductor materials, high recombination rate of electron-hole pairs generated by light, separation problems for the catalyst, and limited activity in complex water matrices are key issues. The interference of suspended solids, inorganic ions, and competing organic substance with light absorption and photocatalytic reactions has to be taken into consideration. In addition, expensive advanced nanostructured catalysts and the demand of energy for artificial irradiation devices can influence the commercial viability. The future study should thus be directed towards the development of less expensive, stable, reusable and sunlight responsive photocatalyst to have better catalytic performance under real wastewater conditions.

The overall discussion indicates that photocatalysis is a green chemistry approach that could be employed to treat wastewater and decrease environmental pollution. Its degradation capabilities for various types of organic contaminants, especially in conjunction with advanced semiconductor materials and renewable energy sources, offer opportunities for sustainable water management. But its efficiency should not be judged just by the pollutant degradation percentage, it should also be judged in terms of mineralization efficiency, reduction in toxicity, stability of the catalyst, operational cost, and environmental safety. Combining photocatalytic methods with other biological and physical approaches could be a viable approach for more effective and environmentally friendly water solutions.

Conclusion

In the field of wastewater treatment, photocatalysis has become a potential and eco-friendly technology to address water pollution issues by applying the principles of green chemistry. Photocatalytic materials can be used to break down a range of organic pollutants, dyes, pharmaceutical waste products, industrial chemicals and other pollutants or contaminants by employing light-driven chemical processes. Photocatalysis also differs from traditional wastewater treatment technologies in that it can help to limit the need for the high levels of chemical additives and can also help to reduce the production of secondary pollutants. The production of advanced photocatalysts, such as nanostructured materials, metal oxides and materials containing semiconductor-based composites has also improved pollutant degradation efficiency, light absorption and

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catalytic stability. Furthermore, the combination of solar energy and photocatalytic process allows the possibility of creating energy-efficient and environmentally friendly wastewater treatment technologies. Though these benefits exist, there are factors such as catalyst recovery, operating expenses, the utilization of visible light only, durability of materials, and commercialization that need to be taken into account. These aspects should be the focus of future research in order to develop reusable and highly efficient photocatalysts, optimise the solar-driven reaction mechanisms and integrate photocatalytic systems into the existing wastewater treatment infrastructures. There is also a need to increase cooperation between researcher, industry and the environmental policy makers to speed up adoption of practical applications and technological development. In conclusion, photocatalysis is a promising green chemistry approach for sustainable water treatment, resource preservation, and environmental remediation, and plays a role in achieving the long-term goal of water security and sustainable development.

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