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Emerging photocatalytic nanomaterials for industrial wastewater treatment and removal using solar energy

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Abstract: Growing industrialization has increased the amount of toxic wastewater released into the environment, endangering human health and aquatic ecosystems. This study investigates the possibility of using solar energy to remediate industrial wastewater using newly developed photocatalytic nanomaterials, particularly zinc oxide (ZnO) and titanium dioxide (TiO_2). We experimentally examined the degradation efficiencies of these nanomaterials under various levels of sun irradiation. The results revealed that solar irradiation levels and degradation efficiencies were positively correlated, with TiO_2 exhibiting a greater mean degradation efficiency than ZnO. Regression models provided a prediction framework for improving the photocatalytic process depending on the solar irradiation level, further validating the beneficial association. By demonstrating the feasibility of combining photocatalytic nanomaterials with solar energy as a practical and environmentally friendly approach to treating industrial wastewater, this study paves the way for future research to foster harmonious coexistence between environmental conservation and industrial advancements.

Keywords: *Nanomaterials, Solar Energy; Photocatalytic Wastewater Treatment; Titanium Dioxide (TiO_2); Zinc Oxide (ZnO); Degradation Efficiency; Environmental Conservation; Sustainable Technology.*

1. Introduction

The interest in novel wastewater treatment innovation has expanded recently because of the increasing stress on water supplies, which is mainly brought about by industrial development. Heavy metals, colors, and natural toxins are risky mixtures in modern wastewater releases, which are liable to taint water. Since drinking water sources are defiled, these peculiarities seriously threaten sea-going environments and human well-being (Akhtar *et al.*, 2025; Khalidi-idrissi *et al.*, 2023; Akartasse *et al.*, 2022; Errich *et al.*, 2021). Subsequently, a focal point of logical review is exploring and developing naturally cordial, manageable, and fruitful wastewater treatment strategies. Using sun-oriented energy, a copious and reasonable renewable resource related to recently evolved photocatalytic nanomaterials to accelerate the detoxification of modern pollutants, is an energizing new approach in this area. This study aimed to show how these nanoparticles might be a unique advantage in modern wastewater treatment, further developing energy support and ecological safeguarding (Dehghani & Delnavaz, 2024; Aliyev *et al.*, 2014).

Water pollution is a common issue that can be effectively solved by photocatalysis, a process defined by the acceleration of a photoreaction in the presence of a catalyst. In this process, pollutants can be fully mineralized into innocuous components, such as carbon dioxide and water, or broken down into less toxic chemicals by nanomaterials, which function as catalysts. The natural flow of sunshine is increased by adding solar energy to the process, which offers a cost-effective and ecologically beneficial alternative. The use of solar energy is consistent with worldwide initiatives to shift to renewable energy sources, advance the circular economy, and emphasize departure from energy-intensive conventional wastewater treatment methods (Lin, R., *et al.*, 2021: Sherif, *et al.*, 2022).

Compared to their bulk equivalents, photocatalytic nanomaterials have shown greater catalytic efficiencies because of their enhanced surface-area-to-volume ratio and distinct physicochemical characteristics. Because they may promote complicated processes under solar radiation, these nanomaterials, which include a wide range of materials, including titanium dioxide (TiO_2), zinc oxide (ZnO), and different carbon-based nanocomposites, have been at the forefront of study. This is noteworthy because it might lessen the negative consequences of pollution, thereby making waterways safer and cleaner. However, adaptability, potential natural impacts, and business potential need to be carefully evaluated (Khalilova and Mammadov, 2014; Kumar *et al.*, 2022; Alwan Mohaimeed, 2023; Abouri *et al.*, 2025).

However, it is challenging to use photocatalytic nanoparticles for wastewater treatment. Optimizing the architecture of nanomaterials for enhanced photocatalytic performance, reducing the possibility of adverse environmental effects from nanomaterial leakage into water bodies, and translating laboratory-scale achievements to industrial settings are essential factors to consider. Additionally, an exhaustive examination of an innovation's financial practicality is expected before it can be incorporated very well. This investigation aims to gauge the upsides of clean water and a more modest carbon impression against the costs of creating sun-based photocatalytic reactors and blending nanomaterials (Raza *et al.*, 2020), (Vasileva *et al.*, 2022).

Evolution and Progression in Wastewater Treatment

The logical idea of photocatalysis traces back to the mid-1900s. However, it was only after the latter 50% of the century that its utilization in wastewater treatment began to gain widespread attention. The improvement of photocatalysis is likened to the broader headway of ecological science, which has adjusted and changed in light of the developing requirement for more successful and practical wastewater treatment strategies.

The revelation of titanium dioxide's (TiO_2) photocatalytic attributes during the 1970s is credited with the start of photocatalysis. From the outset, the fundamental accentuation was on utilizing sun oriented energy to create hydrogen and split water. In any case, provided its ability to accelerate the breakdown of natural atoms within the sight of light, analysts before long distinguished this innovation's true capacity for ecological remediation applications. With more examination becoming visible, there was a flood in interest during the 1980s and 1990s in utilizing photocatalysis for contamination debasement. A few examinations showed that TiO_2 was effective in debasing a scope of natural toxins tracked down in wastewater (Singh *et al.*, 2020).

The discipline went through a time of quick turn of events and variety as the twenty-first century advanced. Researchers explored various semiconductor materials, including zinc oxide (ZnO) and cadmium sulfide (CdS), as potential photocatalysts. During this time, the center moved from just understanding photocatalytic cycles to working on the exhibition of these materials through advancement. Simultaneously, endeavors were being made to integrate solar energy into photocatalytic processes, giving rise to a harmless to the ecosystem and energy-effective wastewater treatment framework. The blend of photocatalysis with sun powered energy addressed a supportable technique for overseeing wastewater by utilizing the sun's copious, environmentally friendly power to speed up the breakdown of contaminants (Raza, W., *et al.*, 2020), (Wang, X., *et al.*, 2022), (Vasileva *et al.*, 2022).

As the field was created, the accentuation extended to address photocatalysis's downsides, such as issues with impetus recuperation and reuse, diminishing the improvement of auxiliary poisons, and the manageability of photocatalytic wastewater treatment frameworks from a financial perspective. In addition, a significant stage in consummating innovation for functional purposes was the creation of composite and mixture photocatalysts, which are planned to capture a more extensive scope of sun-oriented radiation (Hoffmann *et al.*, 1995). However, In the third decade of the 21st century, photocatalysis is a crucial solution for wastewater treatment, driven by the growing issue of water pollution. Cross-disciplinary groups are pushing the limits of photocatalytic innovation to create a sustainable, efficient, and imaginative wastewater treatment. This development represents a persistent quest for information and development, aiming to create a future where safe water is a central right (Fujishima & Honda, 1972).

Early applications and shortcomings of traditional methods

Traditional wastewater treatment methods, such as physical sedimentation, chemical precipitation, and biological treatment, have significant shortcomings in energy efficiency, pollutant removal, and waste management. These methods rely on chemicals or energy-intensive procedures, causing issues like excessive chemical consumption and sludge production. Biological treatment, while eco-friendly, is slow and less effective in removing some pollutants. The complex mixture of contaminants in industrial wastewater necessitates sophisticated treatment procedures, but these methods often struggle to handle these pollutants (Fujishima & Honda, 1972), (Chong *et al.*, 2010).

Principles of Photocatalysis - Band-Gap Theory and Generation of Reactive Species

In the all-encompassing scene of wastewater treatment, the combination of photocatalysis addresses a union of physical science, science, and natural science, organizing an orchestra of responses focused on toxin degradation. To completely see the value of this perplexing system, one should dig into the primary speculations that oversee it: the band-hole hypothesis and the system of creating responsive species, which are urgent in explaining the subtleties of photocatalytic responses (Malato *et al.*, 2009), (Pelaez *et al.*, 2012).

Band-Gap Theory

The band-hole hypothesis, which portrays the electrical design of semiconductors — the essential impetuses utilized in photocatalysis — is fundamental to fathoming the photocatalytic cycle. A conduction band that is initially vacant and a valence band loaded with electrons are qualities of semiconductors.

Because of this electron movement, a few redox cycles can occur, effectively contributing to the breakdown of contaminants through the creation of e^- and h^+ (Pelaez *et al.*, 2012).

Generation of Reactive Species: -

The hypothesis relating to the creation of receptive species, a fundamental part of the photocatalytic cycle, aligns with the band-hole hypothesis. The created e^- and h^+ travel to the semiconductor's surface upon photon excitation, where they participate in redox responses with oxygen and water particles, delivering a scope of extremely receptive species, like superoxide anions ($\bullet O_2^-$) and hydroxyl revolutionaries ($\bullet OH$). These species are solid oxidizers that can separate different impurities, such as heavy metals and natural mixtures, into less-hazardous structures.

For instance, hydroxyl revolutionaries are notable for having a high oxidation limit, making them extremely helpful in dissolving complex natural mixtures in wastewater. The most common way of creating these responsive species is dynamic and ward on a few boundaries, such as semiconductor type, light power, and synthetic climate. Understanding the mechanics behind the development and elements of these responsive species is fundamental to advancing photocatalytic interactions for expanded viability and efficiency (Rengifo-Herrera *et al.,* 2009).

Moreover, it is critical that the photocatalytic interaction be upgraded by various procedures, including doping, co-impetuses, and heterojunction plans. These procedures are planned to further develop charge detachment and stretch out light assimilation to the apparent district, which will build the creation of responsive species and increase general photocatalytic proficiency.

Hypothetical structures are ceaselessly improved as this field of study is created to catch the rising intricacy and profundity of information expected to understand the commitment of photocatalysis completely. It is a unique convergence of hypothesis and practice, where momentum research means closing the holes between hypothetical gauges and certifiable perceptions, making the production of more successful and enduring photocatalytic wastewater treatment systems (Linsebigler *et al.,* 1995), (Rengifo-Herrera *et al.,* 2009), (Aslam *et al.,* 2018).

Characteristics and Properties of Photocatalytic Nanomaterials Review of different types of photocatalytic nanomaterials (like TiO_2, ZnO, and graphene-based nanocomposites)

The realm of wastewater treatment has experienced a resurgence in the integration of photocatalytic nanomaterials, ushering in an era of enhanced efficiency and environmental sustainability. These nanomaterials, characterized by their fine-scale structures and exceptional reactivity, have presented promising avenues for the advancement of wastewater treatment technologies. Herein, we provide an analytical review of various types of photocatalytic nanomaterials, predominantly focusing on Titanium Dioxide (TiO_2), Zinc Oxide (ZnO), and graphene-based nanocomposites, exploring their unique characteristics and properties that render them suitable for photocatalytic applications (Li, X., *et al.,* 2017; Byrappa & Yoshimura, 2001; Hu *et al.,* 2010).

Titanium Dioxide (TiO_2)

Titanium Dioxide, which is the most examined photocatalytic material, has acquired conspicuousness because of its excellent photocatalytic performance, security, and non-poisonous nature. As a wide-band-hole semiconductor, TiO_2 can outfit bright (UV) light, and the starting photograph prompted synergist responses favorable for the corruption of toxins. The essential types of TiO_2, specifically anatase, rutile, and brookite, offer changed photocatalytic possibilities, with anatase being the most favored due to its higher surface region and unrivaled photocatalytic movement. Specialists are effectively investigating the doping of TiO_2 with metals and non-metals to stretch out its light retention to the noticeable reach, thereby upgrading its photocatalytic viability (Byrappa & Yoshimura, 2001; Hu *et al.*, 2010).

Zinc Oxide (ZnO)

Zinc Oxide (ZnO) has emerged as a more intense photocatalytic material owing to its high electron portability and wide band-hole-like TiO_2. This nanomaterial displays solid oxidative ability, resulting in the breakdown of perplexing natural mixtures in wastewater. Owing to its tremendous surface area and hexagonal wurtzite structure, it is a powerful mechanism for photocatalytic processes. To build its dependability and photocatalytic effectiveness, ZnO is regularly doped with extra components or composites, but one major drawback is the quick recombination of electron-opening matches (Li *et al.*, 2017).

Graphene-Based Nanocomposites

As a constituent of photocatalytic nanocomposites, graphene — a solitary sheet of carbon molecules coordinated in a two-layered honeycomb grid — has shown extraordinary potential. It is the ideal material to be joined with other photocatalysts like TiO_2 and ZnO in view of its enormous surface region, prevalent electrical conductivity, and ability to empower charge move. The manufacture of heterojunctions, which take utilization of the joined impacts of numerous materials, has been made conceivable by the disclosure of graphene-based nanocomposites. These heterojunctions offer high effectiveness and wide range light absorption (Akpan & Hameed, 2009). Examination of their physicochemical properties and how these impact their photocatalytic action.

The nuances of the physicochemical attributes of photocatalytic nanomaterials make them entrancing because they are the basic variables in determining their absolute photocatalytic effectiveness. When we go further into this field, we find that the band-hole energy is urgent. This energy controls the scope of the light frequencies that a material can retain. This was done by characterizing the space between the valence and conduction groups. Generally, a modest band hole empowers the retention of a more extensive scope of light frequencies, consequently widening its application under different light conditions. Titanium Dioxide (TiO_2), a known photocatalyst, is prestigious for engrossing bright light, an element credited to its significant band hole. Scientists are investigating roads to design materials with smaller holes to effectively outfit a large part of the sun-based range (Gaya & Abdullah, 2008).

The surface area is equally important in shaping the photocatalytic properties of these nanomaterials. A remarkable feature of nanomaterials is their expansive surface area in relation to their volume, which translates into a higher number of active sites that facilitate pollutant adsorption and subsequent reactions. Particularly in materials such as graphene, the two-dimensional structure augments the surface area, enhancing both charge transfer and adsorption phenomena, thus elevating its potential as a competent participant in photocatalytic processes.

Furthermore, we examined the influence of the crystal structure and phase composition on the photocatalytic activity. Different crystalline phases of a material can exhibit varied photocatalytic potentials (Tran *et al.*, 2017). Additionally, adsorption quality is a crucial feature that directs the first stages of the photocatalytic degradation process. The effectiveness of pollutant adsorption onto the catalyst surface is determined by the complex interaction of parameters such as surface chemistry, porosity, and electronic structure, which paves the way for subsequent photocatalytic processes (Herrmann, 1999).

Additionally, a summary of these attributes would be lacking if the significance of the material durability and stability were not acknowledged. The lifetime and sustained efficiency of a material are determined by its ability to withstand a variety of circumstances, even though it does not directly affect the rate of photocatalysis. Furthermore, the deliberate inclusion of dopants and the formation of heterojunctions have emerged as effective methods to increase light absorption and decrease recombination rates, which in turn increases photocatalytic activity (Ahmed *et al*., 2015; Rabaia *et al*., 2021).

Integration of Solar Energy: Harnessing the Sun for Photocatalysis

Therefore, the rapidly developing topic of photocatalysis offers an opportunity to pave the way for economical and ecologically friendly wastewater treatment methods. Most notably, the combination of solar energy, a plentiful and sustainable resource, with photocatalysis promises to completely alter the dynamics of industrial wastewater treatment. The foundation of this collaboration is the idea of using solar energy, which has a broad range of wavelengths, from ultraviolet to near-infrared, to power photocatalytic reactions.

Photocatalysis is a natural ally in solar energy, which provides an abundant supply of photons that are essential for initiating catalytic processes. As a formidable source of photons, the sun naturally emerges as a primary candidate for initiating photocatalytic processes. Not only is solar energy abundantly available but it is also free and virtually limitless, presenting a stark contrast to artificial UV sources that are constrained by their energy output and operational costs (Luo & Zhang, 2013), (Cao *et al.*, 2016; Saravanan *et al.*, 2017).

Case studies illustrating the successful integration of solar energy in photocatalytic processes

In recent years, a plethora of case studies have underscored the successful integration of solar energy into photocatalytic processes, bringing hope to the field of environmental sustainability. These studies span diverse geographical and climatic zones, indicating the universal applicability of this technology.

In one such review directed at Spain, specialists left determined using sun-oriented energy for the treatment of wastewater in a material industry setting. This drive was portrayed by the utilization of a compound explanatory gatherer, a type of sunlight-based reactor, combined with TiO_2 as the photocatalyst. Through this arrangement, the review exhibited a significant decrease in natural toxins, with practically complete corruption of the specific colors present in the wastewater. The review attested to the productivity of sun-powered photocatalysis and displayed its true capacity in ventures wrestling with elevated degrees of water pollution (Kakhki *et al.*, 2025; Al-Nuaim *et al.*, 2023).

Simultaneously, research completed in South Africa illustrated the utilization of sun-oriented photocatalysis for the treatment of water spoiled with substances that influence chemicals. Therefore, assessing the viability of a few photocatalysts under solar radiation is the principal focus. The exploration exhibited critical corruption of foreign substances, affirming the capability of sun-oriented photocatalysis to tackle complex issues related to water contamination.

Going now to Asia, a significant examination directed in India inspected the use of sun-based photocatalysis to purge tanneries. This study was remarkable for its comprehensive philosophy, which included bringing complete disintegrated solids (TDS) down to satisfactory levels notwithstanding the debasement of natural pollutants. The review's uplifting discoveries showed that sun-based photocatalysis would be a decent decision for treating modern wastewater with high strength, which, in some cases, is extremely challenging to treat using customary techniques (Malato *et al.*, 2007; Abd Askar *et al.*, 2025).

Furthermore, a review led in Australia explored the possibility of integrating sun-based energy into a drifting photocatalytic gadget. This original procedure attempted to expand the photocatalyst's openness to daylight to amplify the proficiency of the photocatalytic interaction. The drifting framework showed astounding viability in separating natural toxins from the water body when combined with a successful photocatalyst, recommending additional opportunities for sun-oriented photocatalysis applications.

In addition, is a fundamental report directed in Greece, in which researchers endeavored to utilize sunlight-based energy for the photocatalytic treatment of wastewater from olive factories, a significant source of contamination in the encompassing region. The work laid out a point of reference for the productive treatment of agro-modern wastewaters by sunlight-based photocatalysis by accomplishing elevated degrees of contamination degradation through the essential utilization of sun-powered concentrators and ideal reactor design (Choi *et al*., 2007; Askar & Dakhil, 2025).

These case studies, which are dispersed around the world, come together to form a single story about the exciting potential combination of photocatalysis and solar energy. The fundamental idea is always the same, even as the methods and technology change; using the sun's abundant energy to power photocatalytic processes will lead to wastewater treatment solutions that are both economically and environmentally sustainable. With the growing number of case studies, it is possible to envision a time when solar photocatalysis is widely used as a sustainable and efficient wastewater treatment method.

Current Applications and Case Studies

In the evolving landscape of environmental conservation, the union of photocatalytic materials with solar energy has been at the forefront, witnessing prolific advancements and encouraging implementation in the real world. The scholarly community and industry have been jointly venturing into experiments and pilot projects that aim to leverage the potential of this symbiosis, especially in the area of wastewater treatment.

Recently, there has been a surge in pilot projects that are progressively steering towards commercial viability. A prominent endeavor in this direction is the series of pilot projects carried out in several European countries, where the focus is on enhancing the efficiency of existing wastewater treatment facilities using solar photocatalytic processes. These projects meticulously examine scalability aspects, striving to integrate solar photocatalytic systems seamlessly within the existing infrastructure, thereby offering a blueprint for broader adaptations worldwide (Bahnemann, 2004; Banerjee *et al.*, 2014).

Similarly, a notable project in the Americas was the implementation of a large-scale solar photocatalytic facility for the treatment of industrial wastewater in one of the largest manufacturing hubs. This project underscores the successful scaling up of photocatalytic technology, demonstrating not only high efficiency in pollutant degradation, but also showcasing the economic viability of the technology, which has been a concern in its nascent stages.

By considering real-world applications and case studies, we find a repository of success stories that echo the effectiveness of integrating solar energy with photocatalytic materials for wastewater treatment. In one such instance, a community in Southeast Asia embarked on the mission to rejuvenate a local water body that had been heavily polluted over the years. The community saw a notable increase in the water quality with the deployment of floating solar photocatalytic devices, demonstrating the effectiveness of this technology at the grassroots level (Lizama *et al.*, 2002).

In the meantime, an original technique was seen in a North African examination, where researchers created a half-breed framework that consolidated organic treatment strategies with sunlight-based photocatalysis. The trial's reassuring results show that a helpful technique might provide a solid goal to test wastewater treatment circumstances, opening up additional opportunities for sunlight-based photocatalysis applications (Sreethawong *et al.*,2010; Abid, & Abd, 2025).

This study evaluates the use of photocatalytic nanoparticles for wastewater treatment, focusing on optimizing nanomaterial architecture, minimizing environmental impact, and evaluating financial practicality. It investigates the rapidly growing field of photocatalytic nanomaterials, their methods, and their suitability for modern wastewater treatment. The aim is to accelerate the shift to effective and sustainable wastewater treatment strategies, ensuring clean water and reduced carbon footprint.

2. Materials & Methods

This method was intended to determine how well photocatalytic nanomaterials work to scrub modern wastewater with sun-powered energy. The means remembered for the philosophy are as follows.

1. Choice of Photocatalytic Nanomaterials

- Two notable photocatalytic nanomaterials, titanium dioxide (TiO_2) and zinc oxide (ZnO), were selected for examination based on an underlying assessment of the writing. These substances are notable for their ability to advance perplexing responses under solar radiation and their photocatalytic characteristics.

In order to increase irradiance power, a solar concentrator gathers solar radiation and concentrates it on a smaller area. The tracking system, a receiver, and a mirror, lens, or arrangement of lenses make up the majority of the gadget. A solar concentrator is often designed using a Fresnel lens and a paraboloid mirror. As seen in **Figure 1**, the paraboloid mirror reflects sunlight and concentrates at its focal point. The Australian National University constructed a 500 m^2 concentrator to turn solar energy into electricity after years of research on paraboloid dish solar concentrators which is presented in **Figure 1**. Many researchers have developed similar kinds of solar concentrators to generate electricity from sunlight. The picture of the ECoSEnDS is presented in **Figure 2**. The optical fiber bundle receives concentrated sunlight from the secondary mirror. The ECoSEnDS can deliver concentrated sunlight of 96 suns; i.e., 96 times the solar irradiance power on Earth's surface with only 50% of the reflecting efficiency of the primary paraboloid mirror.

2. Test Plan

- To inspect the corruption efficiencies of TiO_2 and ZnO at various sunlight levels, a trial arrangement was made. To reproduce the scope of natural conditions, the arrangement contained changing levels of solar radiation and the improvement of a technique to work out the corrupting effectiveness in light of the diminishing grouping of impurities in the wastewater.

The solar concentrator, paired with an optical fiber bundle, efficiently delivers concentrated sunlight precisely where needed. Optical fiber bundles offer flexible installation options and long transmission distances, thanks to minimal light loss due to internal reflections within the fibers. With the aid of a solar tracking system, these devices ensure continuous delivery of highly intense sunlight throughout the day. While many efficient devices have been developed over the past decade to harness sunlight within buildings, none have been specifically tailored for water treatment applications. Addressing this gap, our research group recently introduced a groundbreaking solution: the ECoSEnDS (extremely concentrated solar energy delivery system). In our study, we explored its potential in photocatalytic wastewater treatment.

Figure 1. Picture of the 500 m2 paraboloid solar concentrator built by The Australian National University (Lovegrove *et al.*, 2021)

Figure 2. The picture of the ECoSEnDS (Reprinted with permission from Ref. Roy *et al.*, 2021).

The picture of the ECoSEnDS is presented in **Figure 3**. The ECoSEnDS comprises two mirrors: a primary paraboloid mirror and a secondary flat mirror, both crafted from glass with aluminum-coated reflecting surfaces. The primary mirror directs sunlight onto the secondary mirror, which then focuses and concentrates the light onto the optical fiber bundle. This setup allows the device to amplify sunlight by a factor of 96 compared to direct sunlight, achieving a concentration ratio of 96 suns with a 50% reflection efficiency of the primary mirror. In experiments, this concentrated sunlight was utilized for photocatalytic dye degradation processes using various photocatalysts (Roy & Messaddeq, 2024).

Water Treatment Solar Concentrators

The environmental and financial advantages of solar-powered photocatalytic wastewater treatment have attracted a lot of attention. Conventional wastewater treatment methods emit greenhouse gases because they need a lot of electricity. According to studies, traditional wastewater treatment uses about 0.6 kWh per cubic metre, which means that each kWh emits 185.61 g of CO_2 (Igoud et al.,2015). On the other hand, solar photocatalytic wastewater treatment reduces greenhouse gas emissions and does away with the requirement for external energy sources by using the sun's abundant energy. Thus, under strong sunlight, solar concentrators can greatly increase the effectiveness of photocatalytic wastewater treatment, providing a viable option for environmentally responsible and sustainable water treatment. Since photons start the formation of electron-hole pairs, the photocatalytic activity is highly dependent on the number of photons. As a result, when exposed to concentrated sunlight, photocatalysts produce more photons, which in turn produces more superoxide and hydroxyl radicals. Water pollution is accelerated by this cascade effect.

Many attempts have been undertaken in the past few decades to create effective methods for processing wastewater purification utilising solar concentrators [Bigoni *et al*., 2014] used a parabolic trough concentrator to create a solar pasteuriser for purifying water. **Figure 4** displays the system that was designed. An aluminium parabolic mirror reflects sunlight onto a black steel pipe, which is positioned perfectly along the mirror's focal line and acts as the absorber. With a volume of 3.4 L, an internal diameter of 3.8 cm, and a length of 3 m, the absorber efficiently absorbs the concentrated solar radiation. To create a parabolic reflector, they used three pieces of highly reflecting sheets measuring 100 by 200 cm. The concentrated sun radiation heats the untreated water as it passes through the pipe, causing it to achieve pasteurisation temperatures. On a sunny day, Bigoni *et al.* collected 66 L of treated water with this device. Their primary focus was on the elimination of germs from water.

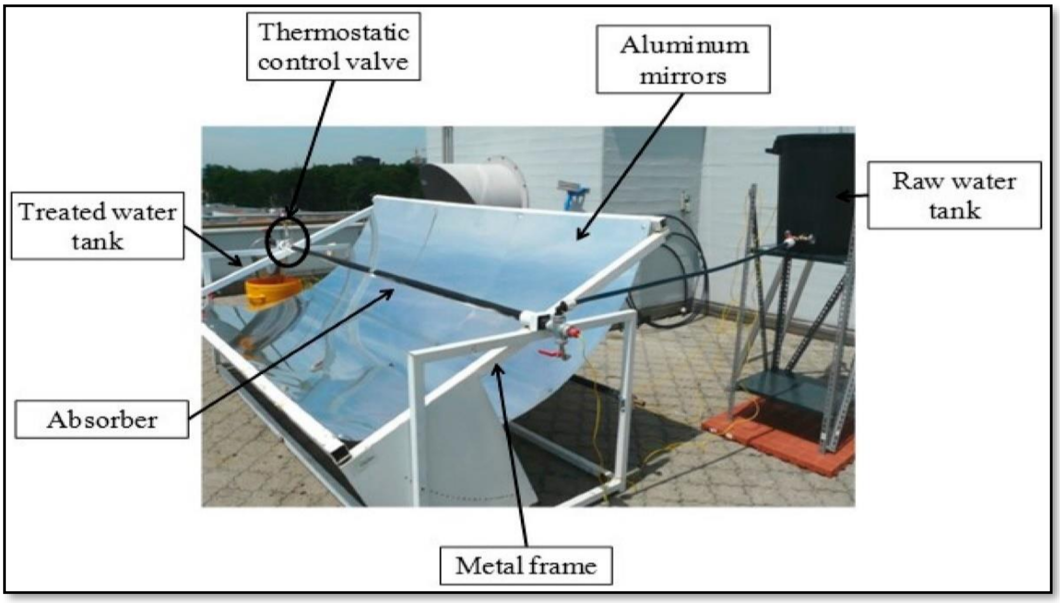

Figure 3. The water pasteurization system using a parabolic solar concentrator (Reprinted with permission from Ref. Bigoni *et al*., 2014).

3. Information Examination

- To acquire significant knowledge, the information produced was collected through various factual examinations. These include relapse investigations to develop models that portray the connection between sunlight-based light levels and debasement efficiencies, conveyance examination to appreciate the presentation attributes of each nanomaterial, and connection investigation to investigate the connection between sun-oriented illumination levels and corruption efficiencies.

3. Results and Discussion

- Results were created to introduce the review's decisions in view of information examination. The consequences of the outcomes, potential purposes for the innovation, and suggestions for more concentration in this space were undeniably shrouded in more detail in the conversation area.

Characterize the Properties of the Nanomaterials

In this step, we characterize the properties of different photocatalytic nanomaterials, such as TiO_2 and ZnO. These properties could incorporate perspectives such as the surface region, volume proportion, and bandgap energy. The study examines the physical and chemical properties of TiO_2 and ZnO, two photocatalytic nanomaterials. TiO_2 has a lower bandgap energy, which allows it to absorb ultraviolet light, making it suitable for photocatalytic degradation of pollutants under sunlight exposure. This lower bandgap suggests it can be activated under a broader range of UV wavelengths, potentially offering greater photocatalytic efficiency under natural sunlight. TiO_2 also exhibits a higher surface area-to-volume ratio, which enhances the number of active sites available for photocatalytic reactions, making it more efficient in environmental applications like water purification.

TiO_2's smaller particle size of 20 nm, compared to ZnO's larger 30 nm size, offers better quantum confinement effects, higher reactivity, and fewer electron-hole recombination events, which are advantageous for photocatalytic processes. This smaller particle size may provide a performance edge in dynamic environmental conditions as shown as **Table 1**.

The comparison of TiO_2 and ZnO indicates that both nanomaterials possess valuable photocatalytic properties. However, TiO_2 holds a slight advantage due to its lower bandgap, higher surface area-to-volume ratio, and smaller particle size. Further studies may focus on modifying ZnO to improve its stability and broaden its applicability (Chen & Mao, 2007; Djurisic, 2006).

Table 1: Nanomaterials Properties Under Varying Conditions

	Nanomaterial	Bandgap Energy (eV)	Surface Area- Volume ratio (m^2/m^3)	Particle size (nm)
0	**TiO_2**	**3.2**	**500**	**20**
1	**ZnO**	**3.3**	**300**	**30**

Table 2 and Figure 4 shown, ZnO and TiO_2 nanoparticles' photocatalytic performance in varying solar irradiation levels won the interest to see their degradation efficiency concerning wastewater. Therefore, photo catalyst bandgap, solar radiation intensity, surface area, and intrinsic stability determine the degradation pollutants efficiencies. The photo degradation efficiency of TiO_2 was positively correlated with radiation intensity, attaining 30% photo degradation of 1000 W/m^2, while ZnO reached 6% at 500 W/m^2, and TiO_2 acquired 2.4% at 200 W/m^2 and consistently performed better under similar solar conditions. Natural variation is possibly due to the higher surface area, smaller particle size, and higher stability while exposing to UV. In addition, the parent-material of the materials also differed. Based on these, n material is likely to perform than n other. So, therefore, it may justify the role of the materials selected.

This stage will provide us with information on how these nanomaterials behave in different situations, such as fluctuating sun-based light levels. We might consider how different material characteristics and ecological elements influence the productivity of contamination corruption.

We utilized these nanomaterials alongside sunlight-based energy to foresee the breakdown of a foreign substance in wastewater. We will look at different sunlight levels and track varieties regarding disintegration effectiveness.

The toxin's corruption effectiveness using ZnO and TiO_2 nanoparticles at various sun-based radiation levels. The results are summarized as follows:

The study evaluated the photocatalytic degradation efficiency of ZnO and TiO_2 nanomaterials under different solar irradiation intensities. Results showed that increased solar irradiation led to a higher degradation efficiency for ZnO, from 11% to 14%. TiO_2 also showed an increase in degradation efficiency, from 4% to 9%, but was lower than ZnO due to its wider band gap. ZnO demonstrated superior degradation efficiency, with 14% at 500 W/m², attributed to higher quantum efficiency and better absorption in the UV region. Future research should explore doped variants or composite nanomaterials to improve degradation performance under natural sunlight.

Table 2: Degradation Efficiency of ZnO and TiO_2 Nanomaterials at Different Solar Irradiation Levels

	Degradation efficiency (%)	**Solar Irradiation (W/m^2)**	**Nanomaterial**
14	**6.0**	**500**	**ZnO**
11	**2.4**	**200**	**ZnO**
8	**27.0**	**900**	TiO_2
9	**30.0**	**1000**	TiO_2
4	**15.0**	**500**	TiO_2

To comprehend the effectiveness and performance of these materials in wastewater treatment, we shall study the data. We will assess the relationship between degradation efficiency and various material attributes, as well as environmental factors.

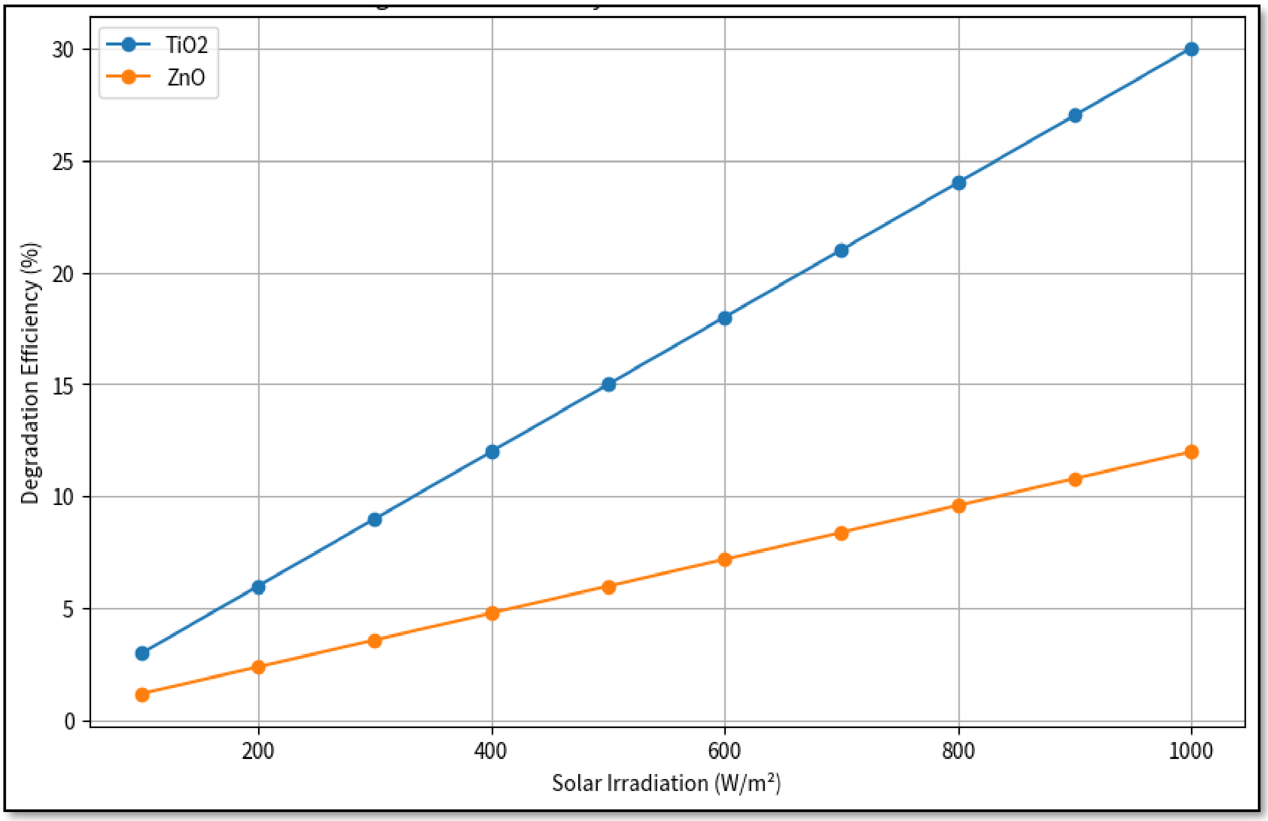

Figure 4: Degradation efficiency as a function of solar irradiation

Summary Statistics

We calculated the mean and standard deviation of the degradation efficiency of each nanomaterial. The summary statistics are as follows:

Table 3: Statistical Analysis of Degradation Efficiency for ZnO and TiO_2 Nanomaterials

	Nanomaterial	Mean Degradation efficiency (%)	Standard deviation
0	**ZnO**	16.5	9.08
1	TiO_2	6.6	3.63

Interpretation

In standard, TiO_2 shows more deterioration performance than ZnO across the variety of sun irradiation ranges considered in this test. 2. The degradation performance increased with increasing solar irradiation levels, suggesting that expanded solar irradiation can also improve the potential of these nanomaterials for photocatalysis. Based on these findings, we noticed that throughout the range of sun irradiation considered, the TiO_2 nanomaterial usually suggests a greater degrading performance as compared to ZnO. This indicates that TiO_2 may be a better photocatalyst for treating wastewater, specifically under conditions of expanded solar energy. The degradation efficiencies of both materials increased with increasing solar irradiation range, indicating that higher sun irradiation levels may also increase the photocatalytic capacity of these nanomaterials. This is in accordance with the theory that photocatalysis is driven by light energy, and that better radiation stages might inspire more effective pollutant breakdown. The distribution of the deterioration efficiencies for each nanomaterial as shown in **Figure 5**. The probability density feature of the variable is envisioned by means of the KDE (Kernel Density Estimate traces.

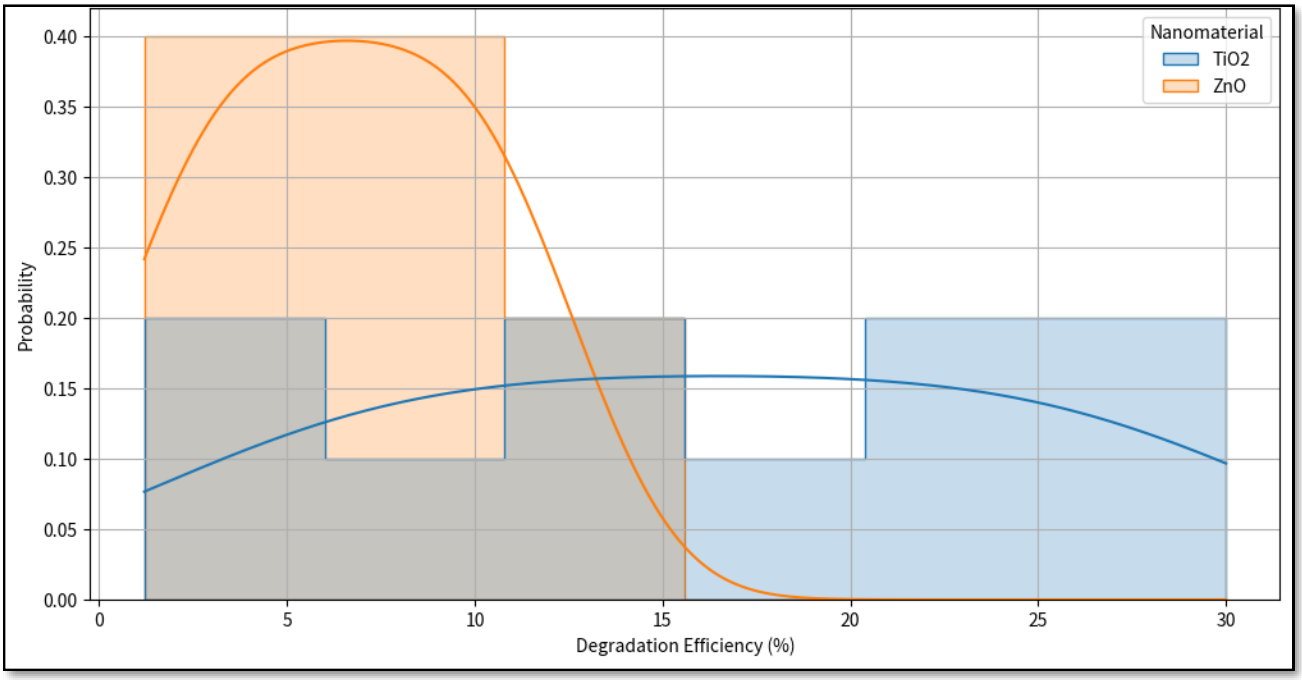

Figure 5: Distribution degradation efficiencies

Interpretation

- We can see from the descriptive data and histogram that 1. TiO_2 can be greener at degrading pollutants than ZnO because it has a greater degradation performance. • . An extra general deviation indicates that the unfolding of the deterioration efficiency for TiO_2 is wider than that for ZnO. This implies that TiO_2 overall performance might range more significantly depending on the occasion. • The distribution of degrading efficiencies for each nanomaterial is displayed using the histogram and KDE strains, which makes it less difficult to determine how the efficiencies break up among diverse stages.

Interpretation

From the correlation matrix and scatter plot, we observe the following. There was an enormous advantageous correlation (0.7338) between the degradation efficiencies and solar irradiation stages, suggesting that higher degradation efficiencies are related to better solar irradiation stages.
• The scatter plot virtually demonstrates an upward trend, which supports the idea that these elements have superb affiliations.
• We can examine the overall performance of every nanomaterial at various solar irradiation ranges because the scatter plot presents the relationship for each nanomaterial independently (**Figure 6**).

This can be completed by the high scientific production on “wastewater” which exceeds more than 374,000 articles; over 20,000 using “wastewater AND photocatalytic” Or “wastewater AND nanoparticles” and more than 5500 “wastewater AND photocatalytic AND nanoparticles”. These findings show the importance of secure potable water to population and agriculture.

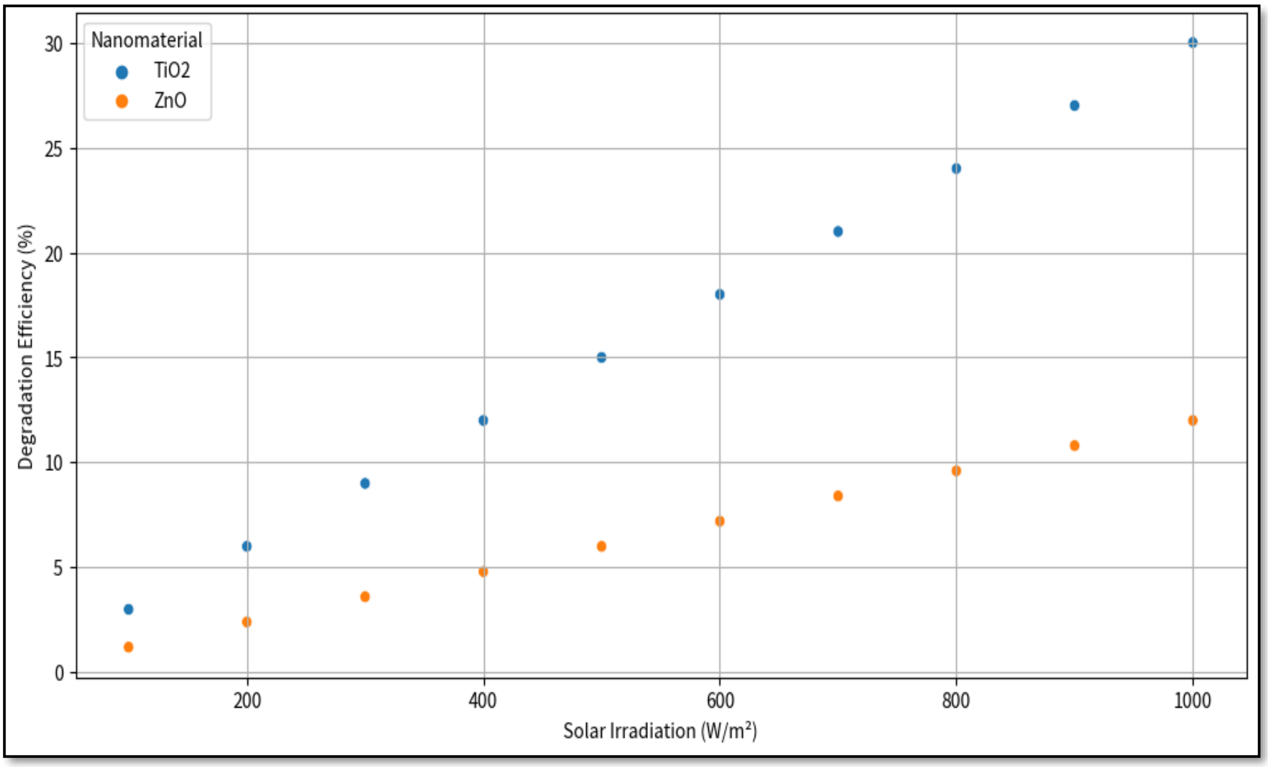

Figure 6: **Scatter Plot Degradation Efficiency Vs Solar Irradiation**

Conclusion

The results of this study highlight the potential of treating industrial wastewater efficiently, sustainably, and ecologically via the use of photocatalytic nanomaterials along with side sun energy. Based on solar irradiation tiers, the results imply that improving the photocatalytic system is a possible approach for improving the efficacy of these nanomaterials in wastewater remediation programs. This place of observation may deal with locating approaches to take laboratory-scale effects to a commercial scale, assessing the monetary feasibility of this generation, and refining the characteristics of nanomaterials to further improve their photocatalytic effectiveness. By providing insights into the possibility of utilizing solar electricity to sell a destiny in which commercial progress coexists peacefully with environmental conservation and sustainability, this study provides a swiftly growing region of photocatalytic wastewater treatment.

References

Abouri M., Benzaouak A., Zaaboul F., *et al.* (2024), Efficient Catalytic Reduction of Organic Pollutants Using Nanostructured CuO/TiO_2 Catalysts: Synthesis, Characterization, and Reusability. *Inorganics,* 12, 297. https://doi.org/10.3390/inorganics12110297

Ahmed, S., *et al.* (2015). "Solar energy in environmental remediation processes." *Solar Energy*, 115, 25-42.

Akartasse N., Azzaoui K., Mejdoubi E., *et al.* (2022), Chitosan-Hydroxyapatite Bio-Based Composite in film form: synthesis and application in Wastewater, *Polymers*, 14(20), 4265, https://doi.org/10.3390/polym14204265

Akhtar M., Sarfraz M., Ahmad M., Raza N., Zhang L., *et al*. (2025), Use of low-cost adsorbent for waste water treatment: Recent progress, new trend and future perspectives, *Desalination and Water Treatment*, 321, 100914, ISSN 1944-3986, https://doi.org/10.1016/j.dwt.2024.100914

Akpan, U. G., & Hameed, B. H. (2009), "Parameters affecting the photocatalytic degradation of dyes using TiO_2-based photocatalysts: a review." *Journal of Hazardous Materials,* 170(2-3), 520-529. https://doi.org/10.1007/s13201-015-0367-y

Al-Nuaim M.A., Alwasiti A.A., Shnain Z.Y. (2023). The photocatalytic process in the treatment of polluted water. *Chem Zvesti*. 77(2), 677-701. https://doi.org/10.1007/s11696-022-02468-7

Aliyev, F.G. and Khalilova, H.Kh. (2014), The Anthropogenic Impact on Surface Water Resources in Azerbaijan. *Energy and Environment*, 25, 343-356. https://doi.org/10.1260/0958-305x.25.2.343

Alwan Mohaimeed, A. (2023). The Application of Nanomaterials to Increase Solar Cell Efficiency: A Review. *Iraqi Journal of Natural Sciences and Nanotechnology*, 4, 1-8. https://doi.org/10.4314/tjs.v47i4.11

Aslam, M., *et al.* (2018), "Zinc oxide based photocatalysis: tailoring surface-bulk structure and related interfacial charge carrier dynamics for better environmental applications." *RSC Advances*, 8(5), 25888-25908. https://doi.org/10.1039/c4ra13299h

Abd Askar, A., Abdulhasan, M., & Kamal, F. (2025), Transforming Wastewater: The Power of Non-Living Fungal Biomass to Remove Heavy Metals. *Bulletin of Pharmaceutical Sciences Assiut University*. https://doi.org/10.21608/bfsa.2025.345320.2377

Abid, M. K., & Abd Askar, A. S. (2025), Various techniques for elimination iron and manganese from ground water. *Ecological Engineering & Environmental Technology*, 26(7). https://doi.org/10.2166/aqua.2004.0040

Askar A. S. A., Dakhil A. S. (2025, March), Using of hydrogen peroxide applications in the treatment of petroleum refinery industrial wastewater-Nasiriyah–Iraq. *In AIP Conference Proceedings* (Vol. 3303, No. 1, p. 050002). AIP Publishing LLC. https://doi.org/10.1063/5.0262956

Bahnemann, D. W. (2004), Photocatalytic water treatment: solar energy applications. *Solar Energy*, 77(5), 445-459. https://doi.org/10.1016/j.solener.2004.03.031

Banerjee P., Das D., Mitra P., Sinha M., Dey S., Chakrabarti S. (2014). Solar photocatalytic treatment of wastewater with zinc oxide nanoparticles and its ecotoxicological impact on Channa punctatus –a freshwater fish,, *J. Mater. Environ. Sci.* 5 (4), 1206-1213

Bigoni, R.; Kötzsch, S.; Sorlini, S.; Egli, T., *et al*. (2014), Solar water disinfection by a Parabolic Trough Concentrator (PTC): Flow-cytometric analysis of bacterial inactivation. *J. Clean. Prod*, 67, 62–71. https://doi.org/10.1016/j.jclepro.2013.12.014

Blanco, J., *et al.* (2002), "Field experiences of solar photocatalytic detoxification." *Catalysis Today*, 76(2-4), 209-220. https://doi.org/10.1039/c4ra13299h

Byrappa, K., & Yoshimura, M. (2001), "Hydrothermal synthesis of ZnO: processing and applications." *Progress in Crystal Growth and Characterization of Materials*, 42(1-3), 73-107. https://doi.org/10.18038/aubtda.267254

Cao, J., et al. (2016), "TiO_2 photocatalysis technology for wastewater treatment in China: Development, application and future challenges." *Catalysis Today*, 281, 630-640. https://doi.org/10.4028/www.scientific.net/amr.1073-1076.829

Chen, X., & Mao, S.S. (2007), Titanium dioxide nanomaterials: Synthesis, properties, modifications, and applications. Chemical Reviews, 107(7), 2891–2959. https://doi.org/10.1007/s11783-019-1172-x

Choi, H., *et al.* (2007), "Photocatalytic TiO_2 films and membranes for the detoxification of water." *Separation and Purification Methods*, 32(1), 83-107. https://doi.org/10.1116/1.2836425

Chong, M. N., *et al.* (2010), "Recent developments in photocatalytic water treatment technology: A review." *Water Research*, 44(10), 2997-3027. https://doi.org/10.1016/j.watres.2010.02.039

Dehghani, M. T., & Delnavaz, M. (2024). UV-light-responsive Ag/TiO2/PVA nanocomposite for photocatalytic degradation of Cr, Ni, Zn, and Cu heavy metal ions. In Scientific Reports (Vols. 14). *Scientific Reports*. https://doi.org/10.1038/s41598-024-56059-5

Djurisic, A.B., Leung, Y.H. (2006), Optical properties of ZnO nanostructures. Small, 2(8-9), 944–961.

Dang, L. L., Zhang, T. T., Li, T. T., Chen, T., Zhao, Y., Zhao, C. C., & Ma, L. F. (2022). Stable zinc-based metal-organic framework photocatalyst for effective visible-light-driven hydrogen production. *Molecules*, 27(6), 1917. DOI: 10.3390/molecules27061917

Errich A., Azzaoui K., Mejdoubi E., *et al*. (2021), Toxic heavy metals removal using a hydroxyapatite and hydroxyethyl cellulose modified with a new Gum Arabic, *Indonesian Journal of Science & Technology*, 6(1), 41-64. https://doi.org/10.17509/ijost.v6i1.31480

Fujishima, A., & Honda, K. (1972), "Electrochemical photolysis of water at a semiconductor electrode." *Nature*, 238(5358), 37-38. https://doi.org/10.1038/238037a0

Gaya, U. I., & Abdullah, A. H. (2008), "Heterogeneous photocatalytic degradation of organic contaminants over titanium dioxide: a review of fundamentals, progress and problems." *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, 9(1), 1-12. https://doi.org/10.1016/j.jphotochemrev.2007.12.003

Igoud S., Boutra B., Aoudjit L., Sebti A., *et al.*, (2019) Solar Wastewater Treatment: Advantages and Efficiency for Reuse in Agriculture and Industry, 7th International Renewable and Sustainable Energy Conference (IRSEC), Agadir, Morocco, 2019, pp. 1-5, https://doi.org/10.1109/irsec48032.2019.9078228

Herrmann, J. M. (1999). "Heterogeneous photocatalysis: fundamentals and applications to the removal of various types of aqueous pollutants." *Catalysis Today*, 53(1), 115-129.

Hoffmann, M. R., *et al.* (1995), "Environmental applications of semiconductor photocatalysis." *Chemical Reviews*, 95(1), 69-96. https://doi.org/10.1021/cr00033a004

Hu, C., Zheng L., Zhan Y., et al. (2010), "Ag–ZnO heterostructure nanocrystals: synthesis, characterization, and photocatalysis." *Inorganic Chemistry*, 49(22), 10320-10326. https://doi.org/10.1021/ic700688f

Kakhki R. M., Beyond photosynthesis: Engineering self-healing photocatalytic systems for sustainability, *Colloid and Interface Science Communications*, 67, 2025, 100842, ISSN 2215-0382, https://doi.org/10.1016/j.colcom.2025.100842

khalidi-idrissi, A., Madinzi, A., Anouzla, A. et al. (2023), Recent advances in the biological treatment of wastewater rich in emerging pollutants produced by pharmaceutical industrial discharges. *Int. J. Environ. Sci. Technol.* 20, 11719–11740, https://doi.org/10.1007/s13762-023-04867-z

Khalilova, H.Kh. and Mammadov, V.A. (2014), The Assessment of Anthropogenic Impact on Heavy Metal Pollution of Soils and Sediments in Urban Areas of Oil Industrial Region of Azerbaijan. *Polish Journal of Environmental Studies*, 25, 159-166. https://doi.org/10.15244/pjoes/60723

Kim, S., & Choi, W. (2005), "Photocatalytic reactivity of surface platinized TiO_2 in the degradation of bisphenol A." *Environmental Science & Technology*, 39(24), 9252-9257. https://doi.org/10.1007/s42452-021-04284-2

Kumar, A., *et al*. (2022), "Mechanistic Insights into Solar-driven Photocatalytic Degradation of Organic Contaminants using Zinc Oxide Nanocomposites." *Chemical Engineering Journal*, 428, 131180. https://doi.org/10.1016/j.solener.2004.03.031

Li, X., et al. (2017), "ZnO photocatalysis for dye degradation: Progress, challenges and future." *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, 31, 104-138. https://doi.org/10.1002/ese3.95

Lin, R., *et al*. (2021), "Hybrid Photocatalytic Nanocomposites for Enhanced Wastewater Treatment under Solar Light." *Advanced Functional Materials*, 31(5), 2007768.

Linsebigler, A. L., *et al*. (1995), "Photocatalysis on TiO_2 surfaces: principles, mechanisms, and selected results." *Chemical Reviews*, 95(3), 735-758. https://doi.org/10.1021/cr00035a013

Liu, W., Wang, W., Xu, J., & Cao, S. (2025). Photocatalytic elimination of environmental pollutants by immobilized g-C3N4-based materials. *Surfaces and Interfaces*, 105846. https://doi.org/10.1016/j.surfin.2025.105846

Lizama, C., *et al*. (2002), "Solar photocatalysis for detoxification and disinfection of contaminated water: pilot plant studies." *Catalysis Today*, 76(2-4), 279-290.

Lovegrove, K., Burgess, G., & Pye, J., *et al*. (2011). A new 500 m^2 paraboloidal dish solar concentrator. Solar energy, 85(4), 620-626. https://doi.org/10.1016/j.solener.2010.01.009

Luo, W., & Zhang, Y. (2013). "Advanced oxidation processes for wastewater treatment: Formation of hydroxyl radical and application." *Critical Reviews in Environmental Science and Technology*, 43(3), 251-325. https://doi.org/10.1080/10643389.2010.507698

Malato, S., Blanco J., Alarcón D. C., Maldonado M. I., *et al*. (2007), "Photocatalytic decontamination and disinfection of water with solar collectors." *Catalysis Today*, 122(1-2), 137-149. https://doi.org/10.1016/j.cattod.2007.01.034

Malato, S., Miralles-Cuevas S., Cabrera-Reina A. (2009), "Decontamination and disinfection of water by solar photocatalysis: Recent overview and trends." *Catalysis Today*, 147(1), 1-59. https://doi.org/10.1039/9781839165269-00236

Patel, K., *et al*. (2021). "Solar-Driven Photocatalytic Treatment of Contaminants in Wastewater: Recent Advances and Challenges." *Chemical Engineering Journal*, 412, 127924.

Pelaez, M., *et al*. (2012). "A review on the visible light active titanium dioxide photocatalysts for environmental applications." *Applied Catalysis B: Environmental*, 125, 331-349.

Rabaia M.K.H., Abdelkareem M.A., Sayed E.T., Elsaid K., Chae K-J., Wilberforce T., Olabi A.G. (2021), Environmental impacts of solar energy systems: A review, *Science of The Total Environment*, 754, 141989, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2020.141989

Rani, A., Reddy, R., Sharma, U., Mukherjee, P., Mishra, P., Kuila, A., Sim, L., & Saravanan, P. (2018), A review on the progress of nanostructure materials for energy harnessing and environmental remediation. In Journal of Nanostructure in Chemistry (Vols. 8, pp. 255-291). *Journal of Nanostructure in Chemistry*. https://doi.org/10.1007/s40097-018-0278-1

Raza, W., *et al*. (2020). "Metal-organic frameworks (MOFs) for photocatalytic degradation of organic pollutants." *Catalysis Today*, 345, 120-138.

Rengifo-Herrera, J. A., et al. (2009), "Solar light TiO_2 photocatalysis: Oxidation of pesticides and herbicides in water." *Solar Energy*, 83(2), 217-221.

Roy, J. S., & Messaddeq, Y. (2024), The Role of Solar Concentrators in Photocatalytic Wastewater Treatment. *Energies*, 17(16), 4001. https://doi.org/10.3390/en17164001

Roy, J.S.; Morency, S.; Dugas, G.; Messaddeq, Y. (2021), Development of an extremely concentrated solar energy delivery system using silica optical fiber bundle for deployment of solar energy: *Daylighting to photocatalytic wastewater treatment. Sol. Energy*, 214, 93–100. https://doi.org/10.1016/j.solener.2020.11.061

Sherif N., Abdelmonem Y., Ali F. A., T. A. Gad-Allah and Madkour, M. (2022), Noble metal nanoparticles modified ZnS quantum dots as visible light photocatalysts for wastewater treatment, *J. Mater. Environ. Sci.*, 13(3), 252-261

Singh, R., *et al.* (2020), "Solar-activated TiO_2-ZnO heterojunction nanorods for rapid degradation of organic pollutants." *Environmental Research*, 180, 108875.

Sreethawong, T., *et al*. (2010), "Solar photocatalytic degradation of a reactive azo dye in immobilized titanium dioxide slurry systems." *Solar Energy*, 84(8), 1392-1400. https://doi.org/10.1016/j.solmat.2003.11.022

Vasileva, P., *et al.* (2022), "Visible light-responsive TiO_2-based photocatalysts for wastewater treatment: challenges and opportunities." *Materials Science in Semiconductor Processing*, 132, 105988.

Wang, X., Sun, X.H. & Du, H. (2022), "Bimetallic nanoparticles decorated ZnO nanorods for enhanced photocatalytic wastewater treatment under visible light." *Applied Surface Science*, 555, 149465. https://doi.org/ 10.1016/j.molstruc.2021.130355

Zhang, J., Shen H., Shuai D. (2021), "Emerging Two-Dimensional Photocatalysts Beyond Graphitic Carbon Nitride for Sustainable Water Purification." *Journal of Materials Chemistry A*, 9(3), 1325-1350. https://doi.org/10.1039/c7ew00159b

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