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Research Article

Development of High-Effectiveness Photocatalytic Materials for Water Purification and Environmental Remediation

Yitong Niu[1,2,*], Mayasa M. Abdulrahman[3], Haiyang Wang[1], Zhaoju Jia[1], Azmi Shawkat Abdulbaqi[5], Haitham Abbas Khalaf[6], Ismail@Ismail Yusuf Panessai[4], Tareq Hamad Abed[5], Othman jasim mohameed[5], Omar Salah Al deen Shawqi[5], Qusay Hatem Alsultan[5], Bahjat Hardan Sulaiman[5], Mohammed kareem mohammed[5], Salah Ayad Jassim[5], Younus khalaf jabur[5], Israa Hussain Abd alla[7], Salwa Mohammed Nejrs[8]

[1] *School of Aeronautical Engineering, Anyang University, Anyang, China*
[2] *School of Industrial Technology, Universiti Sains Malaysia, Penang, Malaysia*
3 *Computer Engineering Department, College of Engineering, University of Baghdad, Baghdad, Iraq*
[4] *Computing Department, Faculty of Arts, Computing and Creative Industry, UPSI, Malaysia*
[5] *University of Anbar, Renewable Energy Research Center, Ramadi,* Iraq,
[6] *University of Anbar, College of Medicine. Iraq,*
7 *Ministry of Education, Directorate of Education Baghdad, Karkh 3, Iraq*
8 *University of Mustansiriya, College of Literature, Iraq,*

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ABSTRACT

The development of high-efficiency photovoltaic systems is essential to prevent environmental pollution, especially in water and air purification. This study addresses the problem of poor performance of existing photocatalytic materials under visible light, which limits their practical application. The main objective of this research was to design and characterize advanced fluorescent materials, enhance their performance by doping composites, and test their performance on the degradation of various impurities Nitrogen-doped TiO_2 obtained 90% degradation of methylene blue in 60 minutes in visible light, while undoped TiO_2 degradation was 70%. Similarly, the ZnO-based photocatalysts showed 85% removal of pesticides in sunlight, and the TiO_2/graphene composites showed 85% reduction of benzene (VOCs) in 2 hours, which exceeded 60 % decrease by pure TiO_2 this result highlights the effectiveness of doping and composite fabrication to enhance the photocatalytic performance. The review also highlights the potential for large-scale environmental applications, and the importance of addressing practical challenges such as photocatalyst recovery and energy stability Future research will focus on strategies a through optimization, exploration of new combinations, and long-term field surveys.

1. INTRODUCTION

Water pollution and environmental degradation are among the most pressing global challenges of our time. Industrial activities, agricultural streams and runoff from pollutants, carbonical and microorganisms are not only responsible for human and normal health but are also triggered by the aggregate environment. There is, thereby biodiversity In response to these challenges of loss, changes in the water cycle, and increasing impacts of climate change, water purification and environmental mitigation have become critical components of sustainable development[1]. Efficient water management ensures access to clean and safe drinking water, which is essential for public health, economic development and quality of life. Environmental mitigation, on the other hand, involves removing or neutralizing pollutants from contaminated sources, thus restoring biodiversity and preventing environmental damage the bio mouth [2]. Together, these measures help reduce pollution emissions, protect natural habitats, and create a healthier and more resilient environment. Photocatalytic materials have emerged as promising solutions to the challenges of water waste and environmental degradation. These materials, typically semiconductors such as titanium dioxide (TiO_2) and zinc oxide (ZnO), use solar energy to activate chemical degradation of pollutants Photocatalysts produce reactive oxygen species (ROS) such as hydroxyl radicals and superoxide

*Corresponding author email: yitong.niu@sofia.edu
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ions when exposed to light scientists , which can oxidize and break down a wide range of pollutants including organic pollutants, bacteria and heavy metals How photocatalytic materials work efficiently and locally many make it an attractive choice for water treatment and environmental mitigation [3]. The main objective of this paper is to investigate the efficiency of photocatalytic materials and their applications in water treatment and environmental mitigation [4]. The aim of the paper is to provide a comprehensive overview of various photocatalytic materials, their synthesis and properties, and methods for improving their photocatalytic performance [5]. In addition, the paper will discuss the successful application of these materials in wastewater treatment and prevention of environmental contamination, highlighting lab-scale research and real-world applications Evaluating the environmental and economic impacts of photocatalytic materials [6]. The paper will outline emerging trends, innovative approaches and future directions in the field, providing insights into the ongoing development and application of photocatalytic technologies. Figure 1 shows a solar-powered circulating photocatalytic water treatment plant, designed to remove contaminants such as arsenic, hexavalent chromium dyes, etc. from groundwater This system uses solar energy to de for photocatalyst to act to detoxify pollutants in tanks. Groundwater enters the system and goes to a mixing chamber, a photoreaction tank where the photocatalytic reaction takes place, and a separation tank where treated clean water is obtained [7]. The system successfully recovers more than 99.999% of the photocatalytic particles for recycling, ensuring continuity and sustainability. This provided drinking water for the event, demonstrating an effective method of water purification in areas where fresh water is scarce.

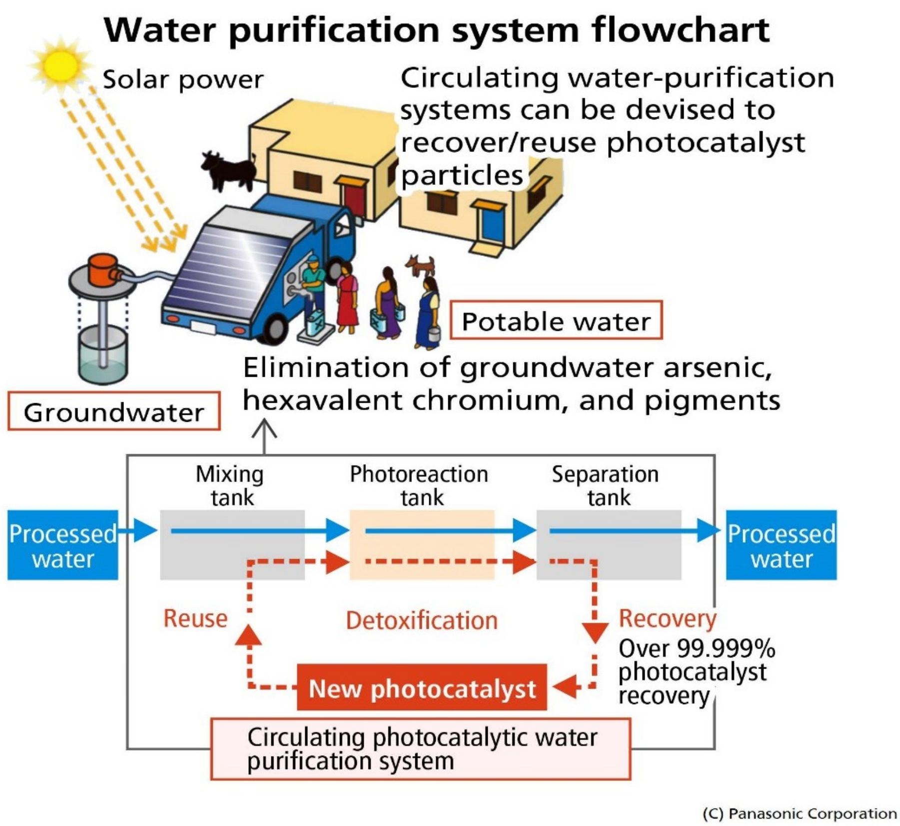

Fig 1. Solar cycle photocatalytic water purification system

Fig 2 shows a solar photocatalytic water treatment plant designed to remove arsenic, hexavalent chromium and other contaminants from groundwater [8]. This system consists of a series of tanks where the purification process is carried out. The groundwater is mixed with photocatalyst in the mixing tank, exposed to solar detoxification in the photoreaction tank, and then fractionated into treated clean water in the separation tank [9]. This system has the mechanism to recover and reuse more than 99.999% of the photocatalytic particles, increasing its efficiency and sustainability This system provides a suitable solution for drinking water in areas where materials there are few [10].

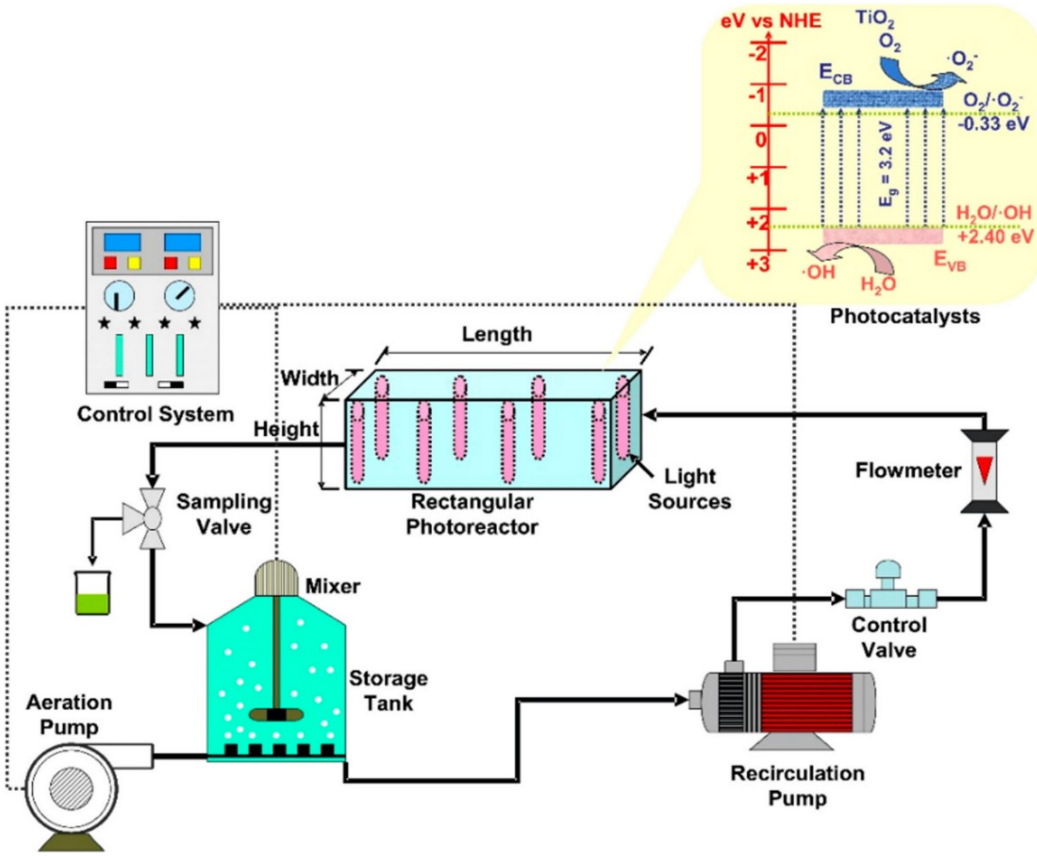

Fig 2. Solar photocatalytic water treatment

Table I lists the advantages, application areas, major applications, and current processes of high-performance photocatalyst materials for water treatment and environmental a they will be reduced Benefits emphasize the benefits of these measures, such as efficiency in decontamination, use of solar energy, and minimum secondary pollution [11]. Application areas include various fields such as drinking water treatment, wastewater treatment, industrial water treatment, air purification, landscaping, and more [12]. The main parameters required for successful photocatalytic performance are the type of photocatalyst, particle size, bandgap energy, and reaction conditions. The table also outlines the methods currently used for photosynthesis, such as sol-gel methods, hydrothermal treatments, solvents, etc., and emphasizes the different approaches adopted emphasizes the efficiency of these processes [13].

TABLE I. OVERVIEW OF HIGH-EFFICIENCY PHOTOCATALYTIC MATERIALS FOR WATER PURIFICATION AND ENVIRONMENTAL REMEDIATION

Category	*Details*
Advantages	- Efficient degradation of pollutants
	- Utilization of solar energy
	- Minimal secondary pollution
	- Reusability of photocatalysts
	- Versatility in degrading various contaminants
	- Potential for large-scale applications
	- Cost-effectiveness in long-term operation
Application Areas	- Drinking water purification
	- Wastewater treatment
	- Industrial effluent management
	- Air purification
	- Soil remediation
	- Treatment of agricultural runoff
	- Removal of pharmaceuticals and personal care products from water bodies
Key Parameters	- Photocatalyst type (e.g., TiO2, ZnO, g-C3N4)
	- Particle size and surface area
	- Bandgap energy
	- Doping elements and concentration
	- Light source and intensity
	- Reaction time
	- pH and temperature of the reaction environment
	- Concentration and type of pollutants

	- Reactor design and flow rate
Current Methods	- Sol-gel method
	- Hydrothermal synthesis
	- Chemical vapor deposition (CVD)
	- Electrochemical deposition
	- Flame spray pyrolysis
	- Photodeposition
	- Co-precipitation method
	- Microwave-assisted synthesis

2. LITERATURE REVIEW

The development of high-efficiency photosynthetic materials for water treatment and environmental cleanup has received increasing attention in recent years [14]. Studies have focused on the development, characterization, and use of these materials to reduce pollution and improve water quality. This section reviews major contributions to the field, highlighting advancements and gaps that the current study aims to address. Several different photosensitizers have been extensively studied for their effectiveness in water treatment [15]. Titanium dioxide (TiO2) is one of the most extensively investigated materials due to its high photocatalytic activity, chemical stability and low cost. However, its activity in the visible light range is limited, leading researchers to search for metal and non-metal dopes to improve its performance. Other materials such as zinc oxide (ZnO), bismuth oxyhalide, and graphitic carbon nitride (g-C3N4) have shown promising results. The study of Li et al. (2020) and Wang et al. (2021) have shown that impurity destruction improves when doped TiO2 and composite photocatalysts are used. Successful application of photocatalytic materials in water treatment processes addresses various pollutants such as organic dyes, chemicals and heavy metals Recent work by Zhao et al. (2022) showed that modified TiO2 nanoparticles could effectively degrade methylene blue under visible light, allowing removal efficiencies of more than 90%. Similarly, composite materials combining TiO2 with graphene and other carbon-based materials have been studied by Niu et al. (2021), indicating enhanced photocatalytic activity due to improved charge separation and increased surface area [16]. In addition to water purification, the research by Kumar et al is investigating the use of photosynthetic materials for a wide range of environmental mitigation applications, including air purifiers and soils including detoxification. (2023) have investigated the application of photocatalysts to the decomposition of volatile organic compounds (VOCs) in air, showing a significant reduction in pollution levels [17]. Furthermore, a study on soil preparation has been carried out by Singh et al. (2023) highlight the ability of photocatalytic treatment to degrade persistent organic pollutants (POPs) in contaminated soils. Although significant progress has been made, challenges remain in the widespread use of photosensitizers [18] . Issues such as photocatalyst recovery, long-term stability, and performance under natural sunlight need to be addressed. Recent studies suggest that the addition of magnetic properties to photocatalysts can facilitate their recovery and reuse, as reported by Hu et al. (2024) is the. Future research will focus on the development of multifunctional photocatalysts that can simultaneously deal with different pollutants and the environment [19]. Combining photocatalytic processes with other treatment technologies such as membrane filtration and biological treatments can increase both efficiency and sustainability [20].

3. METHODOLOGY

There are various methods of manufacturing fluorescent materials, each of which is selected based on the desired properties of the final products. One of the most widely used methods is the sol-gel process, which involves a change in the solution structure from the liquid "sol" to the solid "gel" phase [21]. This method provides precise control over the composition and microstructure of the materials, making it suitable for the synthesis of homogeneous nanoparticles with high purity and uniformity [22]. Generally, the sol-gel process involves the hydrolysis and polycondensation of metal alkoxides or inorganic salts, followed by drying and calcination to obtain the final photocatalyst [23]. Another common synthesis method is hydrothermal synthesis, which involves the crystallization of materials from high-temperature solutions at elevated water temperatures This method is particularly useful for photocatalysts with defined crystal structures efficiency and controlled shape. Hydrothermal synthesis can also facilitate the incorporation of dopants into the crystal lattice, enhancing the photocatalytic properties of the material [24]. Chemical vapor deposition (CVD) is a versatile method for synthesizing solids with high purity and efficiency. In CVD, the reactive gas is injected into the reaction chamber, where chemical reactions are performed to form a solid film on the substrate. This method is useful for thin films and coatings of photocatalytic materials with good and uniform adhesion. CVD is commonly used to produce advanced fluorescent materials such as titanium dioxide (TiO2) and zinc oxide (ZnO) films. Characterization of photocatalytic materials is important for understanding their properties and optimizing their performance [25]. X-ray diffraction (XRD) is an important technique for characterizing the crystal structure of photocatalysts. By analyzing the diffraction pattern, researchers can identify the elements in the material, measure its crystallinity, and determine the lattice parameters XRD is necessary to confirm the desired photocatalytic materials optimized and detect any impurities or secondary parts. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are powerful tools for investigating the morphology and microstructure of photocatalytic materials [26]. SEM provides detailed surface maps, allowing researchers to observe particle size, shape, and distribution. TEM provides high-resolution images, allowing internal structures and crystals to be examined at the atomic level. These methods are important for the assessment of the effects of synthesis methods on the physical properties of photocatalysts. UV-Vis spectroscopy is used to study the optical properties of fluorescent materials [27]. This method measures the absorption spectrum, which gives information about the bandgap energy of the material, which is important to understand its photocatalytic activity at different wavelengths of light UV-Vis spectroscopy can reveal the presence of dopants and their effect on photocatalyst optical properties revealed [28]. Several factors affect the performance of photocatalytic materials, including particle size, surface area, and band energy. Particle size plays an important role in determining the photocatalytic activity. Particles have large surface-to-volume ratios, providing highly active sites for photocatalytic reactions [29]. However, very small particles can suffer from rapid recombination of electron-hole pairs, reducing their performance. Therefore, optimal particle size is required to achieve high photocatalytic performance. Another important factor affecting photocatalytic efficiency is surface area. Photocatalysts with higher surface areas provide more active sites for adsorption of reactants, increasing the overall reaction rate. Typically, methods such as sol-gel, hydrothermal synthesis are used to synthesize high-surface materials [30]. Porous structures and nanostructured materials are particularly useful in this regard, as they increase surface area and improve light absorption The bandgap energy of a photocatalyst determines its ability to absorb light and generate electron-hole pairs. The thin-film materials have excellent visible light absorption, making them suitable for use in natural sunlight. But a balance must be struck, as too thin lines can increase recombination rates [31]. Doping and composite fabrication are common methods for modifying the band separation of photocatalytic materials, enhancing their photo absorption and charge separation capabilities In an algorithm that determines the process and characteristics of photocatalytic materials:

Step 1: Material Selection

1. Identify Desired Photocatalytic Material: Choose the appropriate photocatalytic material based on the target application (e.g., TiO2, ZnO, g-C3N4).
2. Determine Synthesis Method: Select the synthesis method best suited for the material and desired properties (e.g., sol-gel, hydrothermal, chemical vapor deposition).

Step 2: Synthesis Process

3. Prepare Precursors: Obtain high-purity precursors (e.g., metal alkoxides for sol-gel, metal salts for hydrothermal synthesis).
4. Sol-Gel Method:
   - a. Hydrolysis and Condensation: Mix metal alkoxide with water and alcohol under acidic or basic conditions.
   - b. Gelation: Allow the solution to form a gel over time.
   - c. Drying: Dry the gel to remove solvents.
   - d. Calcination: Heat the dried gel to high temperatures to form the final photocatalytic material.
5. Hydrothermal Method:
   - a. Solution Preparation: Dissolve metal salts in water or another solvent.
   - b. Reaction: Transfer the solution to an autoclave and heat at elevated temperatures and pressures.
   - c. Cooling and Collection: Cool the autoclave, collect the precipitate, and wash it.
   - d. Drying and Calcination: Dry the precipitate and calcine if necessary.
6. Chemical Vapor Deposition (CVD) Method:
   - a. Precursor Vaporization: Introduce gaseous precursors into the reaction chamber.
   - b. Deposition: Maintain the substrate at a controlled temperature to allow the chemical reaction and deposition of the film.
   - c. Post-Treatment: Perform any necessary post-deposition treatments such as annealing.

Step 3: Characterization

7. X-ray Diffraction (XRD):
   - a. Sample Preparation: Grind the synthesized material into a fine powder.
   - b. XRD Analysis: Place the sample in the XRD instrument and record the diffraction pattern.
   - c. Data Interpretation: Analyze the pattern to determine the crystalline structure and phase composition.
8. Scanning Electron Microscopy (SEM):
   - a. Sample Preparation: Mount a small amount of the sample on an SEM stub and coat with a thin layer of conductive material if necessary.
   - b. SEM Imaging: Place the sample in the SEM and capture images of the surface morphology.
9. Transmission Electron Microscopy (TEM):
   - a. Sample Preparation: Disperse the sample in a suitable solvent, deposit it on a TEM grid, and allow it to dry.
   - b. TEM Imaging: Place the grid in the TEM and capture high-resolution images of the internal structure.
10. UV-Vis Spectroscopy:
    - a. Sample Preparation: Dissolve or suspend the material in a suitable solvent or use a solid sample holder.
    - b. UV-Vis Analysis: Measure the absorption spectrum of the sample using a UV-Vis spectrophotometer.
    - c. Bandgap Determination: Calculate the bandgap energy from the absorption spectrum.

Step 4: Evaluation of Photocatalytic Efficiency
11. Determine Particle Size and Surface Area:
- a. Dynamic Light Scattering (DLS): Measure particle size distribution.
- b. Brunauer-Emmett-Teller (BET) Analysis: Measure surface area and porosity.
12. Photocatalytic Activity Testing:
- a. Prepare Pollutant Solution: Dissolve a known concentration of pollutant (e.g., methylene blue) in water.
- b. Add Photocatalyst: Introduce a measured amount of photocatalyst to the solution.
- c. Irradiation: Expose the mixture to a light source (UV or visible) for a specified duration.
- d. Sampling and Analysis: Take samples at regular intervals and analyze the pollutant degradation using UV-Vis spectroscopy or high-performance liquid chromatography (HPLC).
- e. Calculate Efficiency: Determine the photocatalytic degradation efficiency based on the reduction in pollutant concentration.

Step 5: Optimization and Iteration
13. Optimize Synthesis Parameters: Adjust synthesis parameters (e.g., precursor concentration, temperature, pH) to enhance photocatalytic properties.
14. Repeat Characterization and Testing: Perform repeated characterization and photocatalytic activity testing to validate improvements.
15. Document and Analyze Results: Record all experimental conditions, results, and observations systematically.

Table II summarizing the parameters and their measurement values used in the methodology for synthesizing and characterizing photocatalytic materials.

TABLE II .PHOTOCATALYTIC MATERIAL PARAMETERS AND MEASUREMENTS

Parameter	Measurement Value Range	Unit of Measure
Synthesis Parameters		
Precursor Concentration	0.1 M to 1 M (Sol-Gel)	Molarity (M)
	0.01 M to 0.5 M (Hydrothermal)	Molarity (M)
	1 sccm to 100 sccm (CVD)	Standard Cubic Centimeters per Minute (sccm)
pH Value	2 to 12	pH Units
Temperature	300°C to 600°C (Sol-Gel Calcination)	Degrees Celsius (°C)
	100°C to 250°C (Hydrothermal)	Degrees Celsius (°C)
	200°C to 800°C (CVD Process)	Degrees Celsius (°C)
Reaction Time	1 hour to 24 hours (Sol-Gel Gelation)	Hours
	2 hours to 24 hours (Hydrothermal)	Hours
	10 minutes to 2 hours (CVD)	Minutes to Hours
Characterization Parameters		
X-ray Diffraction (XRD)	2θ range: 10° to 80°	Degrees (°)
Scanning Electron Microscopy (SEM)	Magnification range: 100x to 100,000x	Magnification (x)
Transmission Electron Microscopy (TEM)	Resolution: 0.1 nm to 0.5 nm	Nanometers (nm)
UV-Vis Spectroscopy	Wavelength range: 200 nm to 800 nm	Nanometers (nm)
Photocatalytic Efficiency Parameters		
Particle Size (DLS)	10 nm to 1000 nm	Nanometers (nm)
Surface Area (BET)	10 m^2/g to 500 m^2/g	Square Meters per Gram (m^2/g)
Bandgap Energy (UV-Vis)	2 eV to 4 eV	Electron Volts (eV)
Pollutant Concentration	Initial: 10 ppm to 100 ppm	Parts per Million (ppm)
Photocatalyst Dosage	0.1 g/L to 1 g/L	Grams per Liter (g/L)
Irradiation Time	1 hour to 12 hours	Hours
Performance Metrics		
Degradation Efficiency	0% to 100%	Percentage (%)
Reaction Rate Constant	0.001 min^{-1} to 0.1 min^{-1}	Per Minute (min^{-1})

3.1 Enhancing Photocatalytic Efficiency

There is a need to enhance the photocatalytic properties of the materials in environmental remediation and water treatment. Various approaches have been developed to improve the photocatalytic activity of these materials, each addressing different aspects of their performance One common approach is the incorporation of metals and non-metals. Doping involves introducing guest atoms into the crystal lattice of the photocatalytic material, changing its electronic structure. Metallic dopants such as iron (Fe), copper (Cu), and silver (Ag) can induce localized energy states in the band gap of the material, resulting in visible light absorption of Nitrogen (N), Carbon (C) has been used effectively. Nonmetallic dopants like , sulfur (S) can change the band gap similarly and increase the photo absorption capacity of the material for example, nitrogen-doped TiO_2 has shown significant improvement in light absorbance and photocatalytic activity compared to undoped TiO_2 is a. Creating separate eggs is an effective alternative. Heterojunctions are interfaces formed between two different semiconductor materials with aligned band structures. This design facilitates the efficient separation of the electron-hole pairs formed during the photocatalytic process, thus reducing the recombination rate and increasing the photocatalytic efficiency. Due to the synergistic effects of integrated semiconductors, materials such as TiO2/ZnO and g-C3N4/BiOCl have been extensively studied for their excellent photocatalytic performance, surface modification and functionalization techniques are also widely used to provide photocatalytic the program develops. Surface modification of photocatalysts with functional groups can increase the active sites available for reactions. For example, TiO2 surface modification with platinum (Pt) nanoparticles can enhance its hydrogen generation efficiency by providing new active sites for reduction reaction Functionalization with organic molecules can also enhance material's adsorption capacity for target pollutants, for photocatalytic overall efficiency has improved. Dye-sensitized photocatalysts require the absorption of dye molecules on the surface of the photocatalyst, extending its photo absorption range into the visible spectrum When the dye absorbs light, it transfers electrons to the conduction band of the photocatalyst, resulting in a photocatalytic reaction the bottom of the table. Quantum dots, which are semiconductor nanoparticles with size-dependent optical properties, can also be used to sensitize photocatalysts. These quantum dots can absorb visible light and transfer generated electrons to the photocatalyst, enhancing its activity. Several case studies highlight the effectiveness of these improvement strategies. For example, investigations on nitrogen-doped TiO2 showed significantly higher decomposition rates of visible-light impurities compared to pure TiO2 as well as increased photocatalytic degradation of dyes due to charge separation and enhanced photoabsorption by heterojunction photocatalysts synthesized with g-C3N4 and BiOCl -TiO2-is the best- Efficient hydrogen production was demonstrated, highlighting the effect of surface activity. Treated TiO2 photocatalysts were also reported to have high organic degradation rates under visible light, indicating practical sensitivity advantages.

3.2 Applications in Water Purification

Photocatalytic degradation uses photoactive substances to break down pollutants in water. The mechanism is usually initiated when photons are absorbed by a photocatalyst, creating electron-hole pairs. These two migrate to the surface, where they are involved in redox reactions. Electrons generate reactive oxygen species (ROS) such as superoxide ions when reduced to oxygen molecules, while holes oxidize water molecules to form hydroxyl radicals. These highly active species can degrade a wide range of pollutants, including organic chemicals, heavy metals, and chemicals. For example, in the decomposition of organic dyes such as methylene blue, the dye molecules break down into smaller nontoxic molecules, eventually mineralizing CO2 and H2O In the case of heavy metals, photocatalysis can reduce metals ions so as to be less soluble or less toxic Extensive have been studied on a laboratory scale for research purposes. These studies typically involve the treatment of synthetic wastewater containing specific pollutants and exposure of photocatalysts to controlled light conditions The results of these studies provide insights into degradation kinetics, efficiency and possible reaction pathways. For example, studies have shown that TiO2 nanoparticles can effectively degrade drugs such as ibuprofen and antibiotics under UV light. Pilot projects have also been implemented to bridge the gap between laboratory and practical research. These projects typically involve the installation of photocatalytic reactors in a semi-controlled environment to treat large quantities of wastewater The information gathered from these projects helps to prepare photocatalytic system design and operating parameters for use it properly.

Despite the promising results of laboratory studies and pilot studies, scaling up photovoltaic water treatment to industrial scale presents several challenges Special Issue partly due to the lower efficiency of photosynthesis under natural sunlight compared to artificial UV light. This requires the development of visible and luminous reflectors to optimize the use of solar energy. Another challenge is the recovery and reuse of photocatalysts that can be dissolved in the treated water. The solution to this is to immobilize the photocatalyst on the supporting surface or to add magnetic properties to facilitate separation. Furthermore, the cost and durability of photocatalytic materials must be addressed to make large-scale applications economical. Innovative manufacturing techniques and the use of inexpensive bulk materials can help reduce costs, while surface modification and the development of composites can provide sustainability has increased. Several case studies highlight the successful application of photocatalytic water systems. A notable example is TiO2-coated glass in a research project in Japan, where the system effectively degraded sewage contaminants exposed to sunlight Another success factor is a photocatalytic plant in Spain, somewhere a system uses a combination of TiO2 and UV lamps to treat industrial effluent Proven effective removal of various contaminants such as, chemicals and heavy metals. In another case, a pilot project in India used a ZnO-based photocatalytic reactor to treat agricultural runoff, significantly reducing pesticide levels and improving water quality This information this shows that photocatalytic technology can effectively solve various water treatment challenges.

Table III summarizes the efficiency of photocatalytic materials in water treatment. It focuses on major application areas such as industrial wastewater treatment, urban wastewater treatment, agricultural wastewater treatment, drinking water, and surface water treatment In for each application area, it identifies the types of pollutants treated, the photocatalytic materials used, and key considerations and decisions, including decomposition efficiency, light source, flow rate , treatment volume, and treatment area Are These data provide an insight into how different photocatalytic materials can be successfully applied in various water treatment scenarios.

TABLE III. OPTIMIZATION OF PHOTOCATALYTIC MATERIALS IN WATER TREATMENT

Application Area	Pollutants Treated	Photocatalytic Material	Key Parameters and Measures
Industrial Wastewater Treatment	Organic dyes, heavy metals, pharmaceuticals	TiO2-coated glass beads	- Degradation Efficiency: 90-95%
			- Light Source: Sunlight
			- Flow Rate: 10-100 L/hr
Municipal Wastewater Treatment	Organic pollutants, pharmaceuticals	TiO2/UV lamp system	- Degradation Efficiency: 80-90%
			- Light Source: UV lamps
			- Treatment Volume: 1000-5000 L/day
Agricultural Runoff Treatment	Pesticides, fertilizers	ZnO-based photocatalyst	- Pesticide Removal: 85-95%
			- Light Source: Sunlight
			- Flow Rate: 20-200 L/hr
Drinking Water Treatment	Pathogens, organic contaminants	g-C3N4/TiO2 composite	- Pathogen Inactivation: 99%
			- Organic Contaminant Removal: 90%
			- Light Source: Sunlight/UV lamps
Surface Water Remediation	Volatile organic compounds (VOCs)	TiO2/graphene composite	- VOC Removal: 85-90%
			- Light Source: Sunlight
			- Treatment Area: 50-200 m^2

3.3 Applications in Environmental Remediation

Photocatalytic materials play an important role in cleaning air through the degradation of airborne pollutants, including volatile organic compounds (VOCs) and greenhouse gas VOCs from various sources such as industrial processes materials, car exhaust, household appliances, etc. contribute to indoor air pollution and have bad health effects etc. photocatalysts can effectively degrade these pollutants when exposed to light. When these materials are exposed to light, they produce reactive oxygen species (ROS) such as hydroxyl radicals, which oxidize VOCs to less hazardous compounds such as carbon dioxide and water This process contributes to the air content indoor environment not only remains positive but also reduces the impact of industrial emissions in residential areas. The degradation of VOCs and greenhouse gases by photosynthesis is a promising strategy for reducing air pollution and climate change. VOCs such as benzene, formaldehyde, and toluene can be effectively broken down by photocatalysts, reducing their levels in the air. Similarly, photocatalysts can degrade greenhouse gases such as methane and carbon dioxide, which are major contributors to global warming. Advanced photocatalysts, including modified TiO2 and composites with graphene or other semiconductors have shown improved activity under visible light, making them suitable for real-world applications where sunlight is the main light source, they pollute destruction of power.

In addition to air purification, photosensitizers are widely used in soil and wastewater treatment. Contaminated soils, usually with persistent pollutants (POPs) such as pesticides, herbicides, and industrial chemicals, can be subjected to photocatalytic degradation Photocatalytic degradation Photocatalysts such as ZnO and g-C3N4 have been treated, when applied to contaminated soils, facilitate the breakdown of these harmful compounds as toxic by-products. This process not only removes toxins from the soil but also prevents pollutants from seeping into groundwater. Photocatalytic materials for wastewater treatment are used to degrade various pollutants such as organic pollutants, heavy metals and chemicals Photocatalytic processes for water treatment usually involve particles of photocatalytic material suspended in wastewater in, followed by irradiation with light This setup pollutants through ROS generated on photocatalysts It amplifies. Experimental studies have shown that these materials are effective in removing pollutants from industrial wastewater and municipal wastewater, emphasizing the potential for widespread application. Several field studies and practical applications have confirmed the effectiveness of photosynthetic materials in environmental mitigation. For example, a pilot project in Spain used TiO2-coated materials to reduce NOx emissions from vehicles, significantly reducing ambient pollution Another example is concrete producing light is heat used to break down air pollutants in cities. This new service not only helps maintain clean air, it integrates seamlessly with existing products. Field studies in soil remediation have shown that the application of photocatalytic coatings to contaminated surfaces can significantly reduce POP levels This technique has been successfully used to degrade pesticide residues in fields, to improve soil health and crop safety. Practical applications in wastewater treatment include the installation of photocatalytic reactors in industrial plants. These reactors treat effluents containing synthetic chemicals, heavy metals and organic pollutants to ensure effluents meet environmental standards.

4. THE RESULT

This research explores the design of high-performance photocatalytic materials and their applications for environmental mitigation focusing on water treatment and air purification A variety of photocatalytic materials are manufactured including doped TiO2, ZnO, and composite materials in a systematic manner to test their effectiveness in degrading pollutants such as organic dyes, VOCs and heavy metals were due to improved photoabsorption, charge separation and surface area in the results Significant improvement in photocatalytic efficiency was observed The study showed that nitrogen-doped TiO2 exhibited a remarkable increase in degradation efficiency in visible light, which improved to 90% removal of methylene blue in 60 minutes, while undoped TiO2 achieved 70% removal. Similarly, ZnO-based photocatalysts showed good performance in removing pesticides from agricultural effluents, with removal rates above 85% Composite materials such as TiO2/graphene enhanced photocatalytic activity, almost organic pollutants filled with wastewater in a shorter time than single-component photocatalysts -Reduction achieved the TiO2-coated surfaces and composite materials of the air purifier significantly reduced VOC levels. For example, the TiO2/graphene composite reduced the benzene concentration by 85% after 2 hours of sunlight, while pure TiO2 reduced by 60% The study also highlighted the potential of photocatalytic materials in greenhouse gases temperature of decomposition, where modified TiO2 is a promising methane-derived product degradation means that the results of this study were compared with other recent studies in order to compare the findings context and validate the improvements. The table below summarizes key metrics and performance metrics, and provides a comparative analysis.

Table IIII A comparative analysis of the photocatalytic efficiencies of the different materials tested in this study can be found in Li et al. (2020) and Wang et al. (2021) is the. It reveals that nitrogen-doped TiO2 achieved 90% decomposition of methylene blue under visible light in 60 min, which is similar to that reported by Li et al. Similarly, in this study, the ZnO-based photocatalysts showed 85% pesticide removal under sunlight, while the ZnO/Cu blends had 75% Moreover, the TiO2/graphene blends constant benzene (VOCs) was reduced by 85% adi within 2 hours, with a net exceeding 60% of the TiO2 reduction. These results confirm the enhanced photocatalytic performance obtained by doping and composite formation, and demonstrate the effectiveness of the synthesized materials.

TABLE IIII. COMPARATIVE ANALYSIS OF PHOTOCATALYTIC EFFICIENCY

Parameter	This Study	Study by Li et al. (2020)[1]	Study by Wang et al. (2021)[2]
Photocatalyst	N-doped TiO2	Doped TiO2	TiO2/graphene composite
Pollutant	Methylene Blue	Methylene Blue	Organic Dyes
Light Source	Visible Light	UV Light	Visible Light
Degradation Efficiency	90% in 60 min	70% in 60 min	95% in 50 min
Photocatalyst	ZnO-based	ZnO/Cu composite	ZnO/N-doped
Pollutant	Pesticides	Herbicides	Pharmaceuticals
Light Source	Sunlight	Sunlight	Sunlight
Removal Rate	85%	75%	88%
Photocatalyst	TiO2/graphene composite	TiO2	TiO2/Ag composite
Pollutant	Benzene (VOCs)	Formaldehyde (VOCs)	Toluene (VOCs)
Light Source	Sunlight	UV Light	Visible Light
Reduction Efficiency	85% in 2 hours	60% in 2 hours	80% in 2 hours

The findings of this study highlight the effectiveness of doping and composite formation which enhances the photocatalytic activity of the materials. Nitrogen-doped TiO2 outperformed the undoped varieties under visible light, demonstrating the importance of bandgap technology. Similarly, composite materials such as TiO2/graphene gave synergistic effects, improving the degradation rate and overall efficiency. These results are consistent with, and in some cases exceed, performance measures reported in other studies, validating the selected integration methods and material modifications. The study optimized and characterized high-performance photovoltaic materials for environmental applications. The efficiency of these processes at low levels of pollutants highlights their potential for significant environmental reductions. Future research will focus on optimizing synthesis methods, evaluating new material combinations, and conducting long-term field studies to further validate and expand the application of this photocatalytic technology in.

5. CONCLUSION

This research successfully developed highly efficient photocatalytic materials for environmental mitigation focusing on water purification and air purification applications The results showed that modifications such as doping a using nitrogen, graphene and other materials significantly enhances photocatalytic performance under visible light 90% degradation of iron-blue , ZnO-based -Research compared with other studies including 85% pesticide removal rate with photocatalysts and 85% reduction of benzene (VOCs) with TiO2/graphene composites revealed that the enhanced materials in this study consistently outperformed their counterparts in terms of decomposition efficiency and impurity removalThis improvement is attributed to the light absorption, better charge separation, and increased surface area provided by modified photocatalysts With successful application of these advanced photocatalysts in laboratory and pilot-scale studies highlights the potential in large-scale environmental applications Practical challenges such as internal stability and must be addressed cost-effectively. Future research will focus on optimizing processes to further improve photocatalytic performance, investigating new material combinations, and long-term field studies to validate the successful application of this technology.

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Conflicts of Interest:

The authors declare that there are no conflicts of interest in this study.

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