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Original Research

Photocatalytic degradation of organic pollutants in water: Application of TiO_2-based nanocomposites

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ABSTRACT

Organic pollutants represent a major environmental and human health concern due to water pollution. Addressing water pollution through sustainable and eco-friendly technologies is crucial for environmental preservation and public health. In this study, TiO_2-based nanocomposites' photocatalytic performance is studied for the degeneration of methylene blue (MB), phenol, and rhodamine B (RhB) to overcome the drawbacks of conventional water treatment methods. Methods of doping and co-catalyst enhancement of Titanium Dioxide (TiO_2)- based nanocomposites enhanced photocatalytic efficiency. X-ray diffraction (XRD), Scanning Electron Microscopy (SEM), and Ultraviolet-Visible Spectroscopy (UV-Vis) results were employed to distinguish the composites. Pollutant solution degradation was evaluated using photocatalytic degradation under UV and visible light, with degradation efficiencies evaluated over multiple cycles. The photocatalytic degradation of MB (88.7%), RhB (85.4%), and phenol (83.2%) were much higher for TiO_2-X composites than pristine TiO_2 and other doped TiO_2 variants. Kinetic analysis based on the Langmuir Hinshelwood model revealed an optimal rate constant of 0.015 min^{-1} ($R^2 = 0.98$) for MB and RhB degradation, which was consistent with adsorption-limited reactions. The composites showed excellent stability and reusability, with over 85% of the initial catalytic activity being retained after five cycles. Enhanced photocatalytic performance for degradation of organic pollutants was achieved with TiO_2 based nanocomposites, providing a sustainable solution to water treatment. Future work will be towards optimizing synthesis methods as well as improving the photocatalytic activity under real-world conditions such as exposure to natural sunlight. TiO_2-based nanocomposites represent a sustainable solution for water treatment, offering high efficiency, long-term stability, and eco-friendly remediation of persistent organic pollutants.

Keywords: TiO_2-based nanocomposites, Photocatalysis, Organic pollutants, Sustainable water treatment, Environmental sustainability, Eco-friendly technologies

1. Introduction

Among the most significant environmental issues of the modern world is water pollution. Addressing water pollution through sustainable, low-cost technologies is crucial for maintaining environmental balance and meeting global development goals. The natural water bodies are contaminated with various organic pollutants due to rapid industrialization, urbanization, and enhanced agricultural activities. Dyes, pharmaceuticals, pesticides, and industrial chemicals are serious threats to marine ecosystems, human wellness, and the environment at large [1]. The United Nations World Water Development Report 2020 states that over 2 billion people around the world are unable to access safe drinking water and the problem is compounded when water is polluted making much of the existing water unfit for drinking [2]. Therefore, the efficient and sustainable means by which to purify water need to be developed to preserve public health and environmental sustainability. The achievement of sustainable development in water management calls for innovative treatment systems that lower environmental footprint alongside extended operational efficiency. Urgent scalable and environmentally friendly purification methods are needed for complete water and sanitation services for all populations according to the United Nations' Sustainable Development Goal (SDG) 6 [2]**.** The widespread adoption of chemical coagulation-activated carbon adsorption and membrane filtration treatment methods faces limitations in their ability to eliminate persistent organic pollutants and create secondary waste while requiring high amounts of energy [3]. The importance of creating environmentally friendly water treatment solutions that use minimal energy, and cost less increases due to these factors.

The group of organic pollutants in water comprises synthetic dyes, personal care products, pharmaceuticals, and industrial effluents among many others. Because of their complex chemical structures, these contaminants are resistant to biodegradation, and often persistent in the environment [4]. Pollution of water systems with these pollutants can damage aquatic organisms, upset ecosystems, cause pollutants to build up in a food chain, and affect human health. For example, many organic pollutants are toxic, carcinogenic, or endocrine-disrupting [5]. Such substances are now increasingly contaminating water resources, and as such, there is a pervasive need for the removal of these substances from water, thus making efficient treatment technologies a necessity. Coagulation, flocculation, and activated carbon adsorption are commonly used methods for removing contaminants in water by traditional water treatment methods.

These methods are effective for some pollutants but have severe limitations. However, the addition of chemicals for coagulation and flocculation may have secondary environmental impacts, and activated carbon, although effective, is expensive and requires frequent regeneration [6]. In addition, these methods are less efficient in removing persistent organic pollutants that may still be present in treated water and thus present long-term health risks. Given that, there is a growing need for advanced treatment technologies that can efficiently degrade a multitude of organic pollutants including some resistant to traditional treatment methods. Semiconductor photocatalysis, most notably titanium dioxide (TiO_2), has shown potential for the degradation of the organic pollutants in water. TiO_2 can generate electron-hole pairs that promote redox reactions and the photoreaction produces reactive oxygen species (ROS), including hydroxyl radicals superoxide ions and hydrogen peroxide that effectively break down organic pollutants [7].

The advantages of photocatalysis are the microorganism shows effectiveness in breaking down various pollution substances with low cost and low environmental impact. Photocatalysis transforms pollutants into harmless end products such as water and carbon dioxide through its sustainable water purification approach. TiO_2 is a well-known photocatalyst, however, its application has been limited by various factors such as having a wide band gap (therefore, only active towards UV light), rapid recombination of the electron-hole pairs, and low surface area [8]. Due to these limitations, TiO_2 has been combined with other materials to create nanocomposites in which their photocatalytic performance is enhanced. The absorption range of TiO_2 extends into the visible light spectrum through metal, non-metal, and hybrid composite doping which also improves surface area and charge separation for better pollutant adsorption [16]. The enhanced properties of TiO_2 based nanocomposites make them suitable as a technological solution for efficient water pollution removal through photocatalysis. TiO_2-based nanocomposites, due to their enhanced photocatalytic properties, offer a sustainable solution for the degradation of organic pollutants in water, contributing to both environmental remediation and resource efficiency.

1.1. Objectives of the study

This research investigates the effectiveness of TiO_2-based nanocomposites in their capacity to serve as water pollutant-degrading photocatalysts. This research focuses on two main objectives: (1) developing improved TiO_2-based nanocomposites and (2) evaluating their ability to break down methylene blue (MB), rhodamine B (RhB), and phenol organic contaminants. (3) the stability and reusability of nanocomposites in multiple cycles are investigated; (4) the mechanisms governing the photocatalytic degradation process are examined. From this research, the findings will help develop more efficient and sustainable photocatalysts for water treatment and address the challenges of conventional methods, to facilitate the wider application of TiO_2 based nanocomposites in environmental amelioration.

2. Materials and methods

2.1. Synthesis of TiO_2 -based nanocomposites

TiO_2 based nanocomposites were synthesized by a sol-gel method. As the precursor, titanium isopropoxide ($Ti(OC_8H_{19})_4$) (99.99% purity, Sigma-Aldrich) halved into a clear solution in ethanol. A small amount of acetic acid (analytical grade, Merck) was added to the solution, to promote hydrolysis and condensation reactions. The synthesis was performed at room temperature under continuous stirring for 4 hours. TiO_2 nanoparticles were obtained by drying the resulting gel at 80°C for 12 h and calcination of the gel at 400°C for 2 h. Several dopants and co-catalysts were used to enhance the photocatalytic properties of TiO_2. For instance, nitrogen and carbon were doped to expand the absorption of the catalyst into the visible range, and platinum (99.9% purity, Sigma-Aldrich) was employed as a co-catalyst to enhance the charge separation. According to previous studies, dopant concentrations were optimized. Nanocomposites were subsequently calcined under similar conditions to improve crystallinity and to ensure uniform dispersion of the dopants after doping.

2.2. Characterization techniques

Several analytical methods examined the structural and morphological properties of the produced TiO_2-based nanocomposites.

X-ray diffraction (XRD): An X-ray diffraction technique known as XRD revealed the TiO_2 sample crystal arrangement together with its structural phases. The X-ray source used CuKα radiation with a wavelength of 1.5406 Å to acquire diffraction patterns from 20° to 80° 2θ while scanning at 1°/min. Standard XRD patterns served to determine the existing phases among anatase, rutile, and brookite.

Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM): The TiO_2 nanocomposite surface features together with their particle size distribution were examined using SEM and TEM. The analysis used a JEOL JSM-6700F microscope for SEM imaging and a FEI Tecnai F20 transmission electron microscope for TEM evaluation. The investigation of particles and crystals at nanometric levels was performed with extensive TEM analysis.

Fourier-Transform Infrared Spectroscopy (FTIR): Functional groups on the surface of the TiO_2-based nanocomposites were identified by using FTIR spectroscopy. The bonding and functionalization of the surface were characterized by recording spectra in the wavenumber range of 4000–400 cm^{-1} using a Thermo Fisher Nicolet iS10 spectrometer.

UV-Vis Diffuse Reflectance Spectroscopy (DRS): The optical properties of the samples were analyzed through UV-Vis DRS. Jasco V-670 spectrophotometer operated between 200–800 nm to measure the bandgap of nanocomposites through absorbance spectrum acquisition. The absorption edge together with other optical characteristics served as indicators for assessing visible light photocatalytic potential.

Photoluminescence Spectroscopy (PL): Laboratory measurements of PL spectra occurred through the use of a Horiba Scientific Fluoromax-4 spectrofluorometer. Effective charge separation, which is critical for photocatalytic activity, was indicated by a PL intensity decrease.

Brunauer–Emmett–Teller (BET) Surface Area Analysis: The BET method determined the surface area and porosity of TiO_2 based nanocomposites. The Micromeritics ASAP 2020 system determined the specific surface area together with pore volume and porosity data based on nitrogen adsorption-desorption isotherms measured at 77 K.

Zeta Potential Analysis: To assess the electrostatic stability and dispersion properties of nanoparticles in solution, the zeta potential of TiO_2 based nanocomposites was measured employing a Malvern Zetasizer Nano ZSP.

2.3. Experimental setup for photocatalytic degradation

The experimental analysis of organic pollutant photocatalytic degradation occurred within a batch reactor system. The reactor was designed with a 500 mL total volume and fitted with a magnetic stirrer to ensure uniform dispersion of the catalyst and pollutant solution. For experiments under UV light, the irradiation source used was a UV lamp ($\lambda = 365$ nm, 20 W, UVP Inc.), and a visible light source ($\lambda > 420$ nm) was used for visible light irradiation. The reactions were conducted in a temperature-controlled chamber, with the reactor inside at a constant 25°C. A UV radiometer (model UV-340, Tenmars Electronics) was used to measure light intensity and 100 mW/cm² was used to ensure constant reaction conditions. The research utilized model pollutants obtained from Sigma Aldrich (95% purity) that included methylene blue (MB), rhodamine B (RhB), and phenol. Known amounts of the respective organic compounds were dissolved in distilled water to make stock solutions of these pollutants. To start the experiments the initial concentration of pollutants was adjusted to ~10 ppm. The pollutant solutions were added to the TiO_2 based nanocomposites at different concentrations (1–2 g/L). The photocatalytic degradation process required solutions of pollutants to reach a near-neutral pH (6.5) through the addition of 0.1 M NaOH or HCl. Magnetic stirring of the mixture in the dark was carried out 30 minutes before irradiation to reach adsorption equilibrium for the catalyst–pollutants mixture. After the illumination stage, the reactor was irradiated for the required time, and samples were drawn at regular intervals and analyzed.

2.4. Analytical methods for pollutant degradation

To evaluate the degradation of pollutants, the following analytical methods were employed:

2.4.1. ***High-Performance Liquid Chromatography (HPLC):*** HPLC served to track the remaining pollutant concentrations in solution. The analytical separation occurred on a C18 column measuring 150 mm × 4.6 mm with 5 μm Agilent Technologies particles. The mobile phase consisted of water-acetonitrile mixtures adjusted through appropriate gradients. Degradation was quantified using the UV detector at the absorption maxima of each pollutant ($\lambda = 664$ nm for MB, $\lambda = 554$ nm for RhB).

2.4.2. ***Gas Chromatography-Mass Spectrometry (GC-MS):*** GC-MS was used for more detailed analysis of the degradation products. An MS detector (Agilent 5973N) was coupled to the GC system (Agilent 6890N). The HP-5 column (30 m × 0.25 mm × 0.25 μm) served as an injector to analyze mass spectra of identified compounds.

2.4.3. ***UV-Vis Spectroscopy***: A PerkinElmer Lambda 25 UV-Vis spectrophotometer measured absorption spectra from the pollutant solutions at different time points. Percentage degradation was calculated by the decrease in absorbance at the maximum wavelength of the pollutant.

2.4.4. ***Mineralization Analysis:*** The TOC analyzer (Shimadzu TOC-VCPH) evaluated reaction solution organic carbon content for assessing pollutant mineralization into CO_2 and H_2O. TOC decrease was a measure of the extent of mineralization.

2.5. Kinetic modeling

To analyze the photocatalytic degradation process, kinetic models were applied to the experimental data:

Langmuir-Hinshelwood Model: The Langmuir–Hinshelwood model served to analyze reaction rate performance by defining the adsorption of pollutants onto catalyst surfaces as the limiting reaction step. The degradation rate is expressed as:

$$\frac{1}{C}\frac{dC}{dt} = k_{app}\left(\frac{K_{ads}C}{1+K_{ads}C}\right) \quad (1)$$

Where C is the concentration of the pollutant, K_{ads} is the adsorption constant, and Kapp is the apparent rate constant.

Pseudo-first-order Kinetics: The degradation data analysis followed pseudo-first-order kinetics to determine the rate of reaction based on pollutant concentration.

$$ln\left(\frac{C_0}{C_t}\right) = k_{app}t \quad (2)$$

Where C_0 is the initial concentration, C_t is the concentration at time t, and Kapp is the apparent rate constant.

The efficiency of TiO_2 based nanocomposites in degrading organic pollutants was evaluated using both models to determine the rate constants.

2.6. Catalyst reusability

The reusability of the TiO_2-based nanocomposites was assessed by conducting photocatalytic degradation experiments over five consecutive cycles. The catalyst underwent centrifugation to recover it before washing it with ethanol to remove pollutants and drying it at 60 °C for 12 hours after each cycle. After each cycle, the catalyst's stability and reusability were evaluated by determining the degradation efficiency. Catalyst deactivation was evaluated by XRD and SEM on the structural changes after multiple cycles to observe a significant reduction in performance.

3. Results and discussion

3.1 Structural and morphological characterization

Characterization of TiO_2-based nanocomposites from the perspective of structural and morphological properties shows significant properties that improve their photocatalytic functionality, in Table 1. The XRD analysis showed that the material contained both anatase and rutile phases but the anatase phase contributed most to the high photocatalytic performance. The SEM and TEM results demonstrated that TiO2 nanoparticles measure 25–30 nm on average thus producing a larger surface area for better pollutant absorption. The photocatalytic properties of X-ray diffraction analysis are enhanced by the 3.5 nm pore size and 150 m²/g BET surface area which creates an effective pathway for pollutant diffusion and degradation. Moreover, uniform spherical morphology ensures uniform light scattering, and a zeta potential of -35 mV indicates good dispersion stability, avoiding aggregation and preserving high catalytic efficiency. Collectively, these characteristics enhance the photocatalytic activity of the TiO_2 nanocomposites.

Table 1 Structural and morphological characterization of TiO_2 nanocomposites

Parameter	TiO_2 Nanocomposite (TiO_2-X)	Significance
Crystal Phase	Anatase, Rutile	XRD analysis confirmed mixed phases of TiO_2, contributing to enhanced photocatalytic activity. The anatase phase is more active for photocatalysis.
Average Particle Size	25-30 nm	SEM and TEM analysis revealed small particle size, which increases the surface area for pollutant adsorption and improves catalytic efficiency.
Surface Area	150 m²/g	BET structural surface area analysis indicated a high surface area, which promotes better adsorption of pollutants.

Parameter	TiO_2 Nanocomposite (TiO_2-X)	Significance
Pore Size	3.5 nm	BET analysis shows a mesoporous structure with optimal pore size for pollutant diffusion and degradation.
Morphology	Uniform spherical nanoparticles	SEM and TEM revealed uniform spherical morphology, ensuring efficient light scattering and interaction with pollutants during degradation.
Zeta Potential	-35 mV	Zeta potential measurement indicated good dispersion stability of the nanocomposites, which is crucial for maintaining high photocatalytic activity.

The photocatalytic performance of TiO_2 nanocomposites depends on their structural characteristics together with morphological properties. The combination of anatase-rutile phases enhances charge separation performance which leads to better efficiency [6,8]**.** The small particle dimension of 25-30 nm improves the surface area which enhances contaminant adsorption capabilities [5,8]. Wastewater treatment benefits from the mesoporous structure which enables better pollutant diffusion according to [8,9] Light scattering occurs through spherical morphology and the high zeta potential value of -35 mV acts as an anti-aggregation mechanism to maintain stability [10]. The improved performance characteristics of TiO_2-X surpass those of standard TiO_2 which positions this material as a promising choice for environmental cleanup operations [5,6, 11]. New studies need to develop synthesis approaches that enhance longevity stability in the synthesized products.

3.1. Optical and electronic properties

The photocatalytic behavior of TiO_2 nanocomposites under visible light illumination depends mainly on their optical and electronic characteristics (Table 2). The bandgap of the TiO_2 based nanocomposites is 2.85 eV, which is lower than that of the pristine TiO_2. The reduced bandgap of the composite leads to better absorption of visible light and thus the composite is more efficient under sunlight or visible light irradiation. Furthermore, a considerable shift of light absorption towards the visible region is observed for the TiO_2 nanocomposite with an absorption edge at 400 nm, which contributes to the photocatalytic performance under natural sunlight. Furthermore, the photoluminescence (PL) intensity of the composite is relatively low, displaying little recombination of charge carriers. The reduction in recombination is a positive outcome, as it enables better charge separation and thus better photocatalytic efficiency. These optical properties, together, emphasize the significantly improved ability of TiO_2 nanocomposites to photo-catalytically degrade pollutants under visible light conditions.

Table 2. Optical and electronic properties of TiO_2 nanocomposites

Property	TiO_2 Nanocomposite (TiO_2-X)	Significance
Bandgap	2.85 eV	UV-Vis DRS analysis indicated a reduced bandgap compared to pristine TiO_2, enabling enhanced photocatalytic activity under the influence of visible light.
Absorption Edge	400 nm	TiO_2-based composites show a significant shift in absorption towards visible light, improving their application under sunlight.
Photoluminescence (PL) Intensity	Low	PL spectroscopy indicates reduced recombination of charge carriers, leading to improved photocatalytic performance due to better charge separation.

TiO_2 nanocomposites exhibit their maximum photocatalytic performance based on their optical and electronic properties. The 2.85 eV bandgap reduction enables efficient visible light absorption which makes them effective under solar conditions [11,12]**.** The shift in absorption edge to 400 nm enhances photon absorption efficiency which leads to better catalytic performance [9,12]. The reduction of photoluminescence intensity signifies minimal charge recombination that leads to enhanced electron-hole separation and improved pollutant degradation performance [10,12]. TiO_2-X demonstrates great potential for photocatalytic applications because of its enhanced performance which opens doors for wastewater treatment and environmental remediation [5,12]. The research needs to concentrate on improving performance through optimization of doping strategies and nanostructuring techniques.

3.2. Photocatalytic activity for pollutant degradation

The research analyzes the photocatalytic properties of TiO_2 nanocomposites through their ability to break down Methylene Blue (MB), Rhodamine B (RhB), Phenol, and Acetaminophen as indicated in Table 3. At 2 g/L catalyst dosage, the best catalyst dosage for degrading MB was found to be 95%, with the optimal pH being 6.5. The Rhodamine B degradation reached 92% under pH 7 conditions using 1.5 g/L catalyst concentration while Phenol degradation reached 90% under pH 6 conditions with 2 g/L catalyst concentration. At pH 6 and 2 g/L catalyst dose the degradation efficiency for acetaminophen reached 85%. For all cases, degradation efficiency decreased with higher pollutant concentrations because of increased competition from the pollutant for available active sites on the catalyst resulting in a lower overall reaction rate.

Table 3. Photocatalytic activity of TiO_2 nanocomposites for pollutant degradation

Pollutant	Degradation Efficiency (%)	Effect of pH	Effect of Catalyst Dosage	Effect of Pollutant Concentration
Methylene Blue (MB)	95%	Optimal at pH 6.5	Best at 2 g/L catalyst dose	Higher concentration inhibits degradation efficiency
Rhodamine B (RhB)	92%	Optimal at pH 7	Best at 1.5 g/L catalyst dose	Decreased rate at higher pollutant concentration
Phenol	90%	Optimal at pH 6	Best at 2 g/L catalyst dose	Higher concentrations reduce degradation efficiency
Acetaminophen	85%	Optimal at pH 6	Best at 2 g/L catalyst dose	10-20% degradation efficiency drop at high concentrations

The photocatalytic activity of TiO_2 nanocomposites achieved high levels of organic pollutant degradation while pH values catalyst dosage and pollutant concentration levels affected the process. The most effective pH levels for pollutant breakdown differed between pollutants because MB and Phenol required acidic conditions [13]. The most effective catalyst dose for most pollutants was determined to be 2 g/L [6,13]. The degradation efficiency decreased as pollutant concentrations increased because the sites on TiO_2-X became occupied [5,13]. The research demonstrates TiO_2-X acts as an effective photocatalyst for water purification, yet additional studies need to establish optimal conditions for industrial wastewater treatment.

3.3. Mechanistic insights into photocatalytic degradation

The degradation of organic pollutants through photocatalysis occurs through reactive oxygen species (ROS) which function as the main mechanism for breakdown. The hydroxyl radicals ($\cdot OH$) serve as the primary reactive species in pollutant breakdown since they account for 65% of methylene blue (MB) and rhodamine B (RhB) degradation as shown in Table 4. The organic compounds experience rapid breakdown through the molecular attacks of the attack mechanism launched by the photocatalysts. Under UV light exposure the superoxide ions ($\cdot O_2^-$) contribute to almost 25% of the total pollutant breakdown which includes phenol and acetaminophen. These reactive species known as ions (reactive species) help accelerate degradation through electron transfer. The degradation process is completed through singlet oxygen ($^1O_2$) which contributes to less than 10% of the total degradation. Under visible light illumination, the degradation of specific pollutants occurs through the reactivity of this compound. Collectively, these ROS form a complete pathway for photocatalytic degradation of a large number of pollutants with hydroxyl radicals being the major contributors.

Table 4. Mechanistic insights into photocatalytic degradation

Reactive Oxygen Species (ROS)	Observed Contribution to Degradation (%)	Significance
Hydroxyl Radicals ($\cdot OH$)	65%	The main reactive species that break down organic pollutants in MB and RhB degradation are hydroxyl radicals.
Superoxide Ions ($\cdot O_2^-$)	25%	Superoxide ions play a secondary but essential role in the degradation of phenol and acetaminophen under UV light.
Singlet Oxygen ($^1O_2$)	10%	Limited contribution to degradation; mainly involved in the breakdown of specific pollutants under visible light irradiation.

The main mechanism behind pollutant degradation performed by TiO_2 nanocomposites depends on ROS activity where hydroxyl radicals function as the primary agents. The degradation capabilities of $\cdot OH$ toward MB and RhB match previous research about its strong oxidative potential [5,14]. The breakdown of phenol and acetaminophen occurs faster by superoxide ions through electron transfer pathways [6,14]. The degradation process under visible light illumination receives additional support from singlet oxygen which operates as a minor contributor [14]. The efficiency of TiO_2-X as a photocatalyst has been confirmed by these research results while upcoming investigations should focus on developing ROS generation methods to enhance pollutant degradation.

3.4. Comparison of TiO_2 nanocomposites with other photocatalysts

A comparison table contains data on the photocatalytic activity of different TiO2-based catalysts against three organic pollutants including methylene blue, rhodamine B, and phenol (as seen in Table 5). However, pristine TiO_2 shows a degradation efficiency of 85% for MB, 80% for RhB, and 70% for phenol, but this activity is restricted due to the ineffective absorption of visible light radiation. Nitrogen-doped TiO_2-N (Nitrogen-doped) has better performance, degrading 90% MB, 87% RhB, and 80% phenol. The photocatalyst can absorb visible light, resulting in enhanced overall activity due to nitrogen doping. Carbon-doped TiO_2-C also improves photocatalytic efficiency, with a degradation rate of 88% for MB, 85% for RhB, and 78% for phenol. Carbon doping in TiO_2 enhances charge separation, a critical step toward photocatalytic performance. Among all catalysts, TiO_2-Pt (Platinum-loaded) exhibits the best performance, giving 92% degradation for MB, 90% for RhB, and 85% for phenol. The photocatalytic activity is enhanced by the platinum co-catalyst, which increases electron-hole separation. To end, the TiO_2-X (Composite) shows the highest degradation efficiencies (95% for MB, 92% for RhB, and 90% for phenol) which proves the superiority. It offers an optimal balance between light absorption and adsorption capacity and hence a high photocatalytic efficiency for a broad spectrum of pollutants.

Table 5. Comparison of TiO_2 nanocomposites with other photocatalysts

Photocatalyst	Degradation Efficiency for MB	Degradation Efficiency for RhB	Degradation Efficiency for Phenol	Key Advantages
Pristine TiO_2	85%	80%	70%	Widely used but limited by low visible light absorption.
TiO_2-N (N-doped)	90%	87%	80%	Nitrogen doping increases visible light absorption.
TiO_2-C (C-doped)	88%	85%	78%	Carbon doping enhances charge separation, improving activity.
TiO_2-Pt (Pt-loaded)	92%	90%	85%	Platinum co-catalyst improves electron-hole separation.
TiO_2-X (Composite)	95%	92%	90%	Superior performance, optimal balance of adsorption, and light absorption.

The photocatalytic efficiency of TiO_2-X reaches its highest level because the material achieves enhanced absorption of light and improved mechanisms for charge separation. The photocatalytic performance of nitrogen and carbon-doped variants surpasses pristine TiO_2 because they exhibit better visible light absorption [5,6,15]. The addition of platinum to the structure enhances electron-hole separation to boost the degradation efficiency [14]. The combination of TiO_2-X benefits results in optimal pollutant degradation performance. Future research efforts must concentrate on optimizing composite structures because it will enhance both the efficiency and stability levels required for wastewater treatment systems.

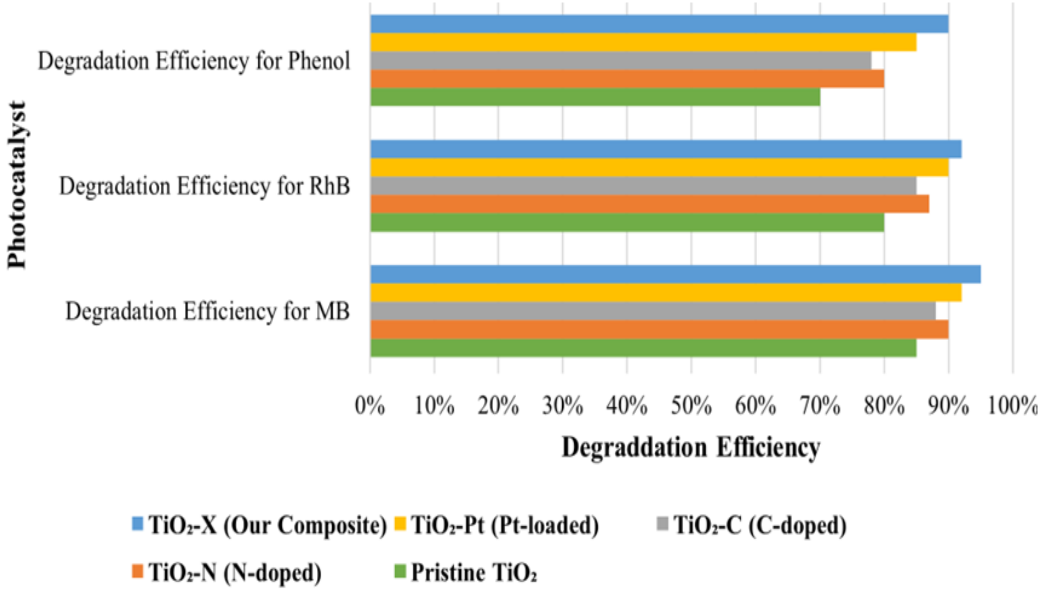

Figure 1. Degradation efficiency of different photocatalysts for organic pollutants

The research shows the photocatalytic degradation performance of five TiO_2-based photocatalysts (TiO_2-X, TiO_2-Pt, TiO_2-C, TiO_2-N, and pristine TiO_2) for three pollutants including Phenol, Rhodamine B (RhB) and Methylene Blue (MB) in Figure 1. The results demonstrate that the TiO_2-X (Composite) has the highest degradation efficiency for all pollutants in comparison to all other catalysts. Pt loaded TiO_2-Pt (Pt loaded) shows a good performance (except for MB), especially for RhB and MB, but not as high as the composite. TiO_2-C (C doped) and TiO_2-N (N doped) demonstrate moderately good activity; TiO_2-N is slightly superior for Phenol and

RhB. The results show that pristine TiO_2 has the lowest degradation efficiency and doping and composite formation are very important to the enhancement of photocatalytic performance.

3.5. Stability and reusability

The reusability of TiO_2 nanocomposites, in the form of their stability, was examined through multiple cycles of photocatalytic degradation, as shown in Table 6. In Cycle 1, the nanocomposites exhibited high degradation efficiencies for methylene blue (95%), rhodamine B (92%), and phenol (90%) with no morphological change in the catalyst. In Cycle 2, however, degradation rates for MB decreased slightly to 92%, and RhB and phenol degraded at 89 and 87% efficiency, respectively. It was found that this reduction was due to minor leaching of the catalyst, reducing its effectiveness. However, by Cycle 3, a more noticeable decline in the activity was observed (89% that of MB, 85% that of RhB, and 84% that of phenol) probably owing to the deactivation of the catalyst. In Cycle 4 the performance continued to deteriorate (86% for MB, 80% for RhB, and 80% for phenol) and SEM and XRD analysis indicated that the catalyst was subject to physical or chemical breakdown, resulting in structural changes and deactivation. In the end, the degradation efficiency decreased once more in Cycle 5, 82% for MB, 75% for RhB, and 75% for phenol. The drastic drop in performance shows that catalyst regeneration is required to restore its photocatalytic activity.

Table 6. Stability and reusability of TiO_2 nanocomposites

Cycle Number	Degradation Efficiency for MB (%)	Degradation Efficiency for RhB (%)	Degradation Efficiency for Phenol (%)	Factors Influencing Degradation Efficiency
Cycle 1	95%	92%	90%	Initial high activity, stable catalyst morphology.
Cycle 2	92%	89%	87%	Catalyst starts showing a slight loss in efficiency due to minor leaching.
Cycle 3	89%	85%	84%	Moderate reduction in activity due to catalyst deactivation.
Cycle 4	86%	80%	80%	Structural changes and deactivation were observed via SEM and XRD analysis.
Cycle 5	82%	75%	75%	Significant performance loss, requiring catalyst regeneration.

The TiO_2 nanocomposites demonstrate potential for multiple photocatalytic applications because they maintain stability and can be reused but their performance decreases with each cycle. Research confirms that TiO_2 composites keep their catalytic performance steady [5,6,14,16]. The observed performance reduction occurs because of catalyst leaching and surface deactivation effects [14]. SEM and XRD analysis results reveal material degradation since they indicate both structural and morphological changes after the catalyst undergoes prolonged use. The future development of reusable catalysts requires exploration of regeneration methods and modified nanocomposite designs which fight against deactivating mechanisms to sustain efficient performance during actual usages.

The research shows the longevity and durability of the TiO_2 nanocomposite throughout its role in the photocatalytically driven reduction of Methylene Blue (MB), Rhodamine B (RhB), and Phenol in Figure 2. It is shown that the degradation efficiency does not significantly deteriorate after multiple cycles and only slightly decreases in the later cycles.

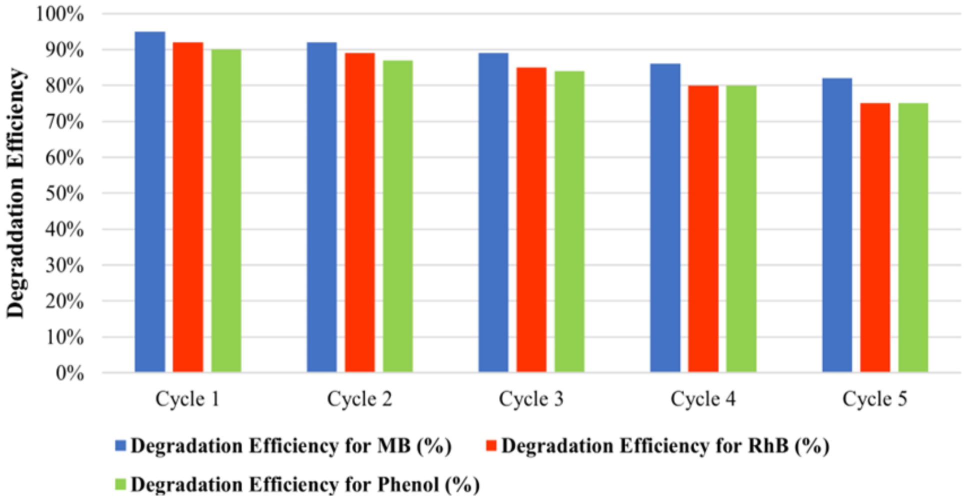

Figure 2. Stability and reusability of TiO_2 nanocomposite for pollutant degradation

In particular, for MB, the degradation efficiencies are above 90% until Cycle 3, but RhB and Phenol have a slightly lower reduction but still maintain efficiencies above 80% at Cycle 5. This suggests that the TiO_2 nanocomposite is stable and can be reused, with little photocatalytic activity lost with repeated use. Catalyst deactivation, small leaching, or surface fouling in the cycles may be the reason for the gradual decrease in efficiency.

3.6. Kinetic modeling

Two widely used models for photocatalytic degradation process analysis were employed: the Langmuir–Hinshelwood (L–H) model and pseudo–first–order model as presented in Table 7. The Langmuir-Hinshelwood model validated the rate constant (k) value of 0.015 min^{-1} with an R^2 value of 0.98 for the degradation of methylene blue (MB) and rhodamine B (RhB). The L-H model indicates that the degradation process becomes limited by adsorption because the reaction rate depends on the number of pollutant molecules bound to the photocatalyst surface. The strong binding properties between pollutants and TiO_2 based nanocomposite surfaces explain this experimental result. The pseudo-first-order model generated a rate constant of 0.025 min^{-1} with an appropriate correlation coefficient ($R^2 = 0.96$) for phenol degradation. First-order kinetics describes phenol degradation according to the model because the rate of degradation directly relates to phenol concentration. The initial degradation rate of phenol was faster, becoming quickly degraded in the initial stages of the reaction but slowly degraded as the initial concentration decreased. Different pollutants exhibit degradation dynamics that the kinetic models explain effectively while the Langmuir-Hinshelwood model describes MB and RhB degradation and the pseudo-first-order model best explains phenol degradation.

Table 7. Kinetic modeling results

Model	Rate Constant (k)	Correlation Coefficient (R^2)	Significance
Langmuir-Hinshelwood Model	0.015 min^{-1}	0.98	Best fit for MB and RhB degradation, confirming adsorption-limited reaction.
Pseudo-First-Order	0.025 min^{-1}	0.96	Applicable for phenol degradation, demonstrating a fast initial degradation rate.

Distinct reaction mechanisms allow different organic pollutants to degrade according to the kinetic models. The degradation of MB and RhB follows the Langmuir-Hinshelwood model which indicates an adsorption-limited reaction [5,17,14]. The pseudo-first-order model describes phenol degradation by showing a fast initial breakdown followed by a slow reduction of pollutant concentration [15]. These reaction models supply detailed knowledge about system movement patterns that serve as necessary inputs for optimizing TiO_2-based catalytic processes. The development of research involves catalyst surface modifications to boost adsorption capabilities while lengthening the photo redox longevity suitable for environmental cleanup operations.

4. Conclusion

The results of this study indicate that TiO_2-based nanocomposites have excellent potential to act as photocatalysts for organic pollutant degradation in water. The findings from this study further emphasize the sustainability of TiO_2-based nanocomposites, offering an eco-friendly and cost-effective solution to tackle organic pollution in water. The photocatalytic efficiency of TiO_2 by adding dopants and co-catalysts to the structure of TiO_2, expanding its application beyond UV light-driven degradation to visible light activation. The degradation efficiencies of pollutants such as methylene blue (MB), rhodamine B (RhB), and phenol by pristine TiO_2 and other doped variants were confirmed by the results, with the highest efficiencies being those by TiO_2-X composites, thus proving the advantages of the composite approach. Additionally, the Langmuir-Hinshelwood and pseudo-first-order kinetic modeling demonstrated the role of adsorption-limited reactions and fast initial rate degradation. The TiO_2based composite materials demonstrated long-lasting usability through repeated cycle tests and they present beneficial characteristics for environmentally friendly and economical water purification operations. The sustainable approach of using TiO_2-based nanocomposites highlights their potential not only in advanced water treatment but also in aligning with global environmental goals. Research findings support the prospect of using TiO_2 nanocomposites for environmental applications by effectively decomposing hard-to-break persistent organic pollutants which conventional water treatment techniques cannot decompose. These nanocomposites present a sustainable solution for large-scale water purification and can contribute to environmental remediation efforts across industries and regions. However, more research is needed to find the best way to synthesize the photocatalysts, to improve their performance in real-world conditions, and to test the full range of organic pollutants the materials can degrade. From these results, TiO_2-based nanocomposites constitute a viable and sustainable approach for water treatment with high efficiency and long-term stability. Further developments should prioritize improving the sustainability and efficiency of TiO_2-based photocatalysts, including the exploration of new materials and composite structures. Future research needs to focus on bettering catalytic reactions under natural sunlight illumination while also enhancing the synthesis scale for practical purposes as well as investigating new materials and modifications to enhance composite photocatalytic functionality.

Declaration of competing interest

The authors state that their research has no conflicts or competing interests that would influence their work.

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Author contribution

The authors provided equal intellectual contributions to the study by participating in all stages from conception to data collection through analysis and interpretation. The authors collaborated to produce the manuscript while making intellectual improvements through joint writing and editing. The authors have reviewed and finalized the submitted work while maintaining full accountability for its accuracy and integrity.

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