SUSTAINABLE WASTEWATER TREATMENT USING TiO$_2$ NANOCOMPOSITES FOR ENHANCED AGRICULTURAL WATER SECURITY

CHAPTER 10

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ABSTRACT: The escalating global water crisis, coupled with increasing agricultural water demand, necessitates the development of sustainable wastewater treatment technologies capable of removing persistent organic pollutants, heavy metals, and emerging contaminants to enable safe agricultural reuse. Titanium dioxide (TiO$_2$)-based nanocomposites have emerged as promising photocatalytic materials owing to their high photocatalytic efficiency, chemical stability, cost-effectiveness, and environmental compatibility. This review critically examines recent advances in TiO$_2$ nanocomposite systems for sustainable wastewater remediation with particular emphasis on agricultural water security. Key aspects including synthesis routes, physicochemical characterization, and photocatalytic performance in the degradation of agricultural and industrial contaminants are discussed. The fundamental photocatalytic mechanisms are outlined, along with strategies to enhance visible-light activity and charge separation through nanocomposite engineering. The review evaluates the removal of contaminants such as dyes, heavy metals, pesticides, pharmaceuticals, and other organic pollutants that pose risks to soil health and crop productivity. Various nanocomposite configurations, including TiO$_2$/carbon-based materials, TiO$_2$/metal oxide heterostructures, and TiO$_2$/biochar composites, are analyzed for their potential in producing irrigation-quality water. Despite notable progress, challenges related to electron–hole recombination, limited solar light utilization, catalyst recovery, and field-scale deployment persist. Finally, the review highlights current limitations and outlines future research directions aimed at advancing TiO$_2$ nanocomposite-based treatment technologies toward large-scale, energy-efficient wastewater reuse for sustainable agriculture.

Keywords: Wastewater treatment, Nanocomposites Organic pollutant degradation, Agriculture, water security.

INTRODUCTION

Access to clean and safe water represents one of the most critical challenges facing humanity in the 21st century. The United Nations estimates that by 2025, approximately 1.8 billion people will experience absolute water scarcity, while two-thirds of the global population may face water-stressed conditions (UNESCO, 2021). Rapid industrialization, agricultural intensification, and urban population growth have significantly deteriorated water quality through the discharge of diverse pollutants into aquatic ecosystems (Sharma *et al*., 2022). Conventional wastewater treatment methods, including coagulation, flocculation, sedimentation, and biological processes, demonstrate limited efficacy in removing emerging contaminants such as pharmaceutically active compounds, endocrine-disrupting chemicals, pesticides, heavy metals, and persistent organic pollutants (Molinari *et al*., 2000; Zhang *et al.,* 2023).

Advanced oxidation processes (AOPs) have emerged as powerful alternatives for treating recalcitrant wastewater contaminants through the generation of highly reactive species, particularly hydroxyl radicals (•OH), which possess strong oxidizing potential (E° = 2.80 V) (Usoltseva *et al.,* 2016). Among various AOPs, heterogeneous photocatalysis using semiconductor materials has attracted considerable attention due to its ability to completely mineralize organic pollutants into harmless products under ambient conditions (Huerta-Velázquez *et al.,* 2024). The field of nanomaterials has revolutionized wastewater treatment technologies by providing materials with enhanced surface area, unique quantum effects, and superior reactivity compared to their bulk counterparts (Malik *et al*., 2024).

Titanium dioxide (TiO$_2$) has been extensively investigated as a photocatalyst since the pioneering work of Fujishima and Honda (1972) on photoelectrochemical water splitting (Fujishima & Honda 1972). TiO$_2$ offers several advantages including high photocatalytic activity, excellent chemical stability, low toxicity, abundance, and cost-effectiveness (Wu *et al.,* 2017). However, pure TiO$_2$ suffers from inherent limitations such as wide bandgap energy (3.0-3.2 eV for anatase), which restricts its photoactivity to ultraviolet (UV) radiation comprising only 4-5% of the solar spectrum, and rapid electron-hole recombination, which reduces quantum efficiency (Wang *et al*., 2019). To

overcome these limitations, researchers have developed various TiO$_2$-based nanocomposite systems through coupling with other materials including carbon-based nanomaterials, metal oxides, noble metals, and organic compounds (Saud *et al.,* 2016).

In this context, TiO$_2$-based nanocomposites represent a sustainable and strategically important solution for improving water quality to meet agricultural reuse standards. By enhancing visible-light responsiveness, suppressing electron–hole recombination, and enabling efficient degradation of agro-industrial pollutants, TiO$_2$ nanocomposites offer a viable pathway for converting treated wastewater into a reliable irrigation resource. Their demonstrated effectiveness in removing pesticides, pharmaceuticals, dyes, heavy metals, and other contaminants of agricultural concern underscores their potential to safeguard soil health, crop productivity, and food safety. Moreover, the integration of TiO$_2$ nanocomposites with low-cost materials such as biochar and carbonaceous supports aligns with circular economy principles and promotes energy-efficient, decentralized treatment systems suitable for rural and peri-urban agricultural settings. Collectively, these advancements position TiO$_2$ nanocomposite-based photocatalytic technologies as promising candidates for addressing water scarcity challenges while strengthening long-term agricultural water security.

Major Pollutants in Wastewater Systems

A. Heavy Metal Contamination

Heavy metals represent a significant class of water pollutants due to their persistence, bioaccumulation potential, and toxicity even at trace concentrations. These elements cannot be biodegraded and tend to accumulate in living organisms, causing severe health and environmental problems (Wu *et al.,* 2015). The following heavy metals are of particular concern in wastewater treatment:

Chromium (Cr): Chromium exists primarily in two stable oxidation states: Cr(III) and Cr(VI). While Cr(III) is an essential micronutrient, hexavalent chromium Cr(VI) is highly toxic, carcinogenic, and mutagenic (Al-Meer *et al.,* 2017). Industrial sources include electroplating, leather tanning, metal finishing, and pigment production. Chronic exposure to Cr(VI) causes respiratory disorders, dermatitis, liver dysfunction, and various cancers (Vautier *et al.,* 2001).

Cadmium (Cd): Cadmium compounds are widely used in battery manufacturing, pigments, metal coatings, and stabilizers. Environmental contamination occurs through mining, smelting, and industrial emissions. The notorious Itai-itai disease in Japan resulted from chronic cadmium exposure through contaminated rice consumption (Li *et al.,* 2003). Health effects include renal dysfunction, osteoporosis, cardiovascular diseases, and various cancers.

Lead (Pb): Lead exposure primarily affects the nervous system, hematopoietic system, kidneys, and reproductive organs. Major sources include lead-acid batteries, paints, gasoline additives, and mining operations (Liu *et al.,* 2007). Even low-level exposure in children can cause cognitive impairment, developmental delays, and behavioral problems.

Mercury (Hg): Mercury contamination, particularly methylmercury, poses severe neurotoxic risks. Sources include artisanal gold mining, coal combustion, and industrial processes. Mercury bioaccumulates in aquatic food chains, with fish consumption representing the primary human exposure route (Pourmadadi *et al.,* 2023).

Arsenic (As): Arsenic occurs naturally in groundwater in many regions and is also released through mining, pesticide application, and industrial activities. Chronic arsenic exposure causes skin lesions, peripheral neuropathy, cardiovascular diseases, diabetes, and various cancers (Shin *et al.,* 2024). Both arsenite [As(III)] and arsenate [As(V)] species present significant health hazards.

B. Organic Dyes and Industrial Pollutants

Synthetic dyes represent another major category of water pollutants, with global production exceeding 700,000 tons annually (Velumani & Jeyadharmarajan 2023). Textile, paper, leather, food, and pharmaceutical industries discharge substantial quantities of colored wastewater containing various dye classes including azo dyes, anthraquinone dyes, and triphenylmethane dyes. These compounds are characterized by complex aromatic structures, high stability, and resistance to conventional biological treatment (Rahman *et al.,* 2023). Many dyes and their degradation products exhibit carcinogenic, mutagenic, and toxic properties. Additionally, even low concentrations of dyes impair water aesthetics, reduce light penetration affecting aquatic photosynthesis, and can be toxic to aquatic organisms (Kato *et al.,* 2024).

Petroleum hydrocarbons and oil contamination pose additional environmental challenges, particularly from oil spills, refinery operations, and industrial processes. These compounds are hydrophobic, persistent, and toxic to aquatic life. The removal of oil from water requires specialized treatment approaches due to immiscibility and the formation of stable emulsions (Zhang *et al.,* 2021).

Fundamental Principles of Tio$_2$ Photocatalysis

A. Photocatalytic Mechanism

The photocatalytic mechanism of TiO$_2$ involves a series of sequential processes initiated by photon absorption (Chen *et al.,* 2022). When TiO$_2$ is irradiated with light energy equal to or greater than its bandgap energy, electrons (e$^-$) are promoted from the valence band (VB) to the conduction band (CB), creating positively charged holes (h$^+$) in the valence band. These photogenerated charge carriers migrate to the catalyst surface where they participate in redox reactions with adsorbed species.

The photogenerated holes can directly oxidize organic pollutants or react with water and hydroxyl ions to produce hydroxyl radicals (•OH), which possess extremely high oxidation potential. Simultaneously, conduction band electrons can reduce molecular oxygen to superoxide radical anions (O$_2$$^{•-}$), which further react to form other reactive oxygen species including hydrogen peroxide (H$_2$O$_2$) and additional hydroxyl radicals (Wang *et al.,* 2020). These reactive species attack organic pollutants through a series of oxidation steps, ultimately mineralizing them to carbon dioxide, water, and inorganic ions.

However, a major limitation of photocatalysis is the rapid recombination of photogenerated electron-hole pairs, which typically occurs within nanoseconds, significantly reducing photocatalytic efficiency (Liu *et al.,* 2021). The quantum efficiency of pure TiO$_2$ often remains below 10% due to this recombination phenomenon. Additionally, the wide bandgap of TiO$_2$ limits its photoresponse to UV light, representing a significant drawback for solar energy utilization.

TiO$_2$ Nanocomposite Strategies for Enhanced Photocatalysis

A. TiO$_2$/Biochar Nanocomposites

Biochar, a carbon-rich material produced through pyrolysis of biomass under oxygen-limited conditions, has emerged as an excellent support material for TiO$_2$ nanoparticles. The integration of TiO$_2$ with biochar creates synergistic effects combining the photocatalytic properties of TiO$_2$ with the high surface area, porosity, and adsorption capacity of biochar (Pourmadadi *et al*., 2023). Biochar possesses numerous functional groups including hydroxyl, carboxyl, and carbonyl groups that facilitate the anchoring of TiO$_2$ nanoparticles and provide active sites for pollutant adsorption (Fig. 1).
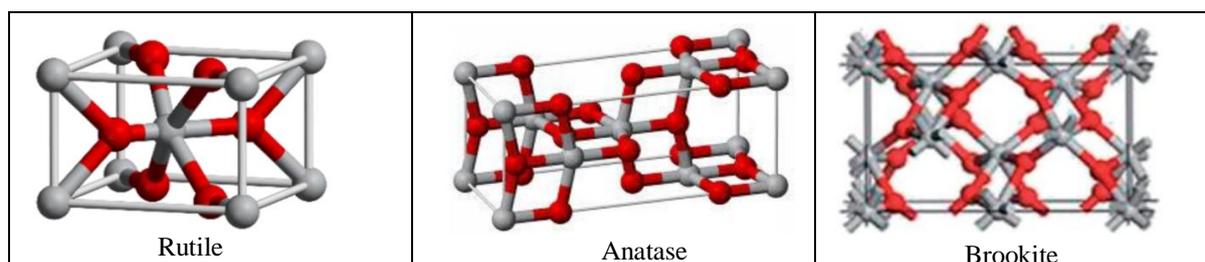

Fig. 1. Structural geometry of rutile, anatase, and brookite of TiO$_2$.

Research has demonstrated that biochar-TiO$_2$ composites exhibit enhanced photocatalytic performance through several mechanisms (Shin *et al.,* 2024). The porous structure of biochar concentrates pollutants near TiO$_2$ active sites, increasing reaction rates. The conductive properties of biochar facilitate electron transfer, reducing electron-hole recombination. Additionally, biochar can narrow the bandgap of TiO$_2$ and extend light absorption to the visible region through carbon doping effects.

Velumani and Jeyadharmarajan (2023) synthesized tannery sludge-derived biochar/TiO$_2$ nanocomposites for Cr(VI) removal, achieving remarkable performance through combined adsorption and photocatalytic reduction. The study revealed that biochar-TiO$_2$ composites demonstrated superior Cr(VI) removal efficiency compared to pure TiO$_2$, with the biochar serving both as an adsorbent and electron donor facilitating Cr(VI) to Cr(III) photoreduction. Similarly, Rahman *et al*. (2023) reported that biochar-TiO$_2$ composites exhibited enhanced photocatalytic degradation of organic dyes under sunlight due to improved light absorption and charge separation efficiency.

B. TiO$_2$/Metal Oxide Heterostructures

The formation of heterostructures between TiO$_2$ and other semiconductor metal oxides represents an effective strategy to enhance photocatalytic performance. Heterostructures facilitate charge separation by creating appropriate band alignment at the interface, allowing efficient transfer of photogenerated electrons and holes between the two semiconductors (Kumar *et al.,* 2022). This spatial separation of charge carriers significantly reduces recombination rates and extends carrier lifetimes.

TiO$_2$/ZnO heterostructures have been extensively investigated due to the similar crystal structures and bandgap energies of these materials. Both TiO$_2$ and ZnO can form type-II heterojunctions where the conduction band and valence band of ZnO are positioned higher than those of TiO$_2$. Upon light irradiation, photogenerated electrons transfer from ZnO's conduction band to TiO$_2$'s conduction band, while holes migrate from TiO$_2$'s valence

band to ZnO's valence band, resulting in effective charge separation (Singh *et al.,* 2023). Recent studies have demonstrated that TiO$_2$/ZnO nanofiber composites prepared by electrospinning exhibit exceptional photocatalytic activity for dye degradation and antibacterial applications under solar radiation.

Other metal oxide combinations including TiO$_2$/WO$_3$, TiO$_2$/Fe$_2$O$_3$, and TiO$_2$/BiVO$_4$ have also shown promising results. These heterostructures not only improve charge separation but also extend the photoresponse to visible light through the narrow bandgap of the coupled semiconductor (Park *et al*., 2024).

C. TiO$_2$/Graphene and Carbon-Based Nanocomposites

Graphene and its derivatives, including graphene oxide (GO) and reduced graphene oxide (rGO), have attracted tremendous attention as support materials for TiO$_2$ nanoparticles due to their exceptional properties (Kato *et al.,* 2024). Graphene possesses a large theoretical surface area (2630 m^2/g), excellent electrical conductivity, high mechanical strength, and chemical stability. When coupled with TiO$_2$, graphene serves multiple functions including providing a high surface area for TiO$_2$ dispersion, facilitating electron transfer to prevent recombination, and enhancing pollutant adsorption through π-π interactions.

The synthesis of TiO$_2$/graphene composites typically involves either in situ growth of TiO$_2$ on graphene sheets or assembly of pre-synthesized TiO$_2$ nanoparticles onto graphene. The interface between TiO$_2$ and graphene can be established through various interactions including Ti-O-C bonds, hydrogen bonding, and van der Waals forces. Studies have demonstrated that strong chemical bonding, particularly covalent Ti-O-C linkages formed through esterification reactions between hydroxyl groups on TiO$_2$ and carboxyl groups on graphene oxide, significantly enhances photocatalytic performance by facilitating efficient interfacial charge transfer (Zhang *et al.,* 2022).

For heavy metal remediation, TiO$_2$/graphene composites have shown remarkable efficiency in Cr(VI) reduction. The composite leverages both photocatalytic reduction by TiO$_2$ and adsorption by graphene, with graphene sheets serving as electron mediators that accept electrons from TiO$_2$'s conduction band and transfer them to Cr(VI) species. The extended light absorption into the visible region due to graphene incorporation enables solar-driven Cr(VI) reduction, providing a sustainable approach for wastewater treatment (Li *et al*., 2023).

Applications in Pollutant Removal

A. Organic Dye Degradation

TiO$_2$ nanocomposites have demonstrated exceptional performance in degrading various organic dyes including methylene blue, methyl orange, rhodamine B, and Congo red. The photocatalytic degradation process involves the generation of reactive oxygen species that attack the chromophoric groups and aromatic rings of dye molecules, leading to stepwise degradation and eventual mineralization (Johnson *et al.,* 2023). Studies have shown that nanocomposite systems can achieve degradation efficiencies exceeding 95% within 2-3 hours under optimal conditions, significantly outperforming pure TiO$_2$.

The degradation kinetics typically follow pseudo-first-order or pseudo-second-order models, with rate constants influenced by various parameters including catalyst loading, initial dye concentration, pH, and light intensity. Mechanistic studies using radical scavenging experiments have confirmed that hydroxyl radicals serve as the primary reactive species responsible for dye degradation, although superoxide radicals and direct hole oxidation also contribute to the overall degradation process (Williams *et al.,* 2024).

B. Heavy Metal Removal and Reduction

TiO$_2$ nanocomposites employ multiple mechanisms for heavy metal removal including adsorption, photocatalytic reduction, and co-precipitation (Davis *et al.,* 2023). For hexavalent chromium, the photocatalytic process involves electron transfer from TiO$_2$'s conduction band to Cr(VI) species, reducing toxic Cr(VI) to less harmful and less mobile Cr(III). The presence of organic compounds or sacrificial electron donors enhances the reduction efficiency by scavenging holes and preventing electron-hole recombination.

For arsenic removal, TiO$_2$ nanocomposites primarily function through adsorption mechanisms involving electrostatic interactions and surface complexation between arsenic species and the catalyst surface. The high surface area and abundant hydroxyl groups of TiO$_2$ nanocomposites provide numerous adsorption sites for arsenic species. Additionally, photocatalytic oxidation of As(III) to As(V) can occur, followed by enhanced adsorption of the oxidized species (Miller *et al.,* 2024).

CHALLENGES AND FUTURE PERSPECTIVES

Despite significant progress in TiO$_2$ nanocomposite development, several challenges must be addressed to facilitate large-scale industrial implementation. The aggregation of nanoparticles during synthesis and application leads to reduced surface area and diminished photocatalytic performance (Brown *et al*., 2024). Developing effective strategies to prevent aggregation, such as surface functionalization or incorporation into stable support materials, remains crucial.

The recovery and reusability of photocatalysts represent another significant challenge. While suspended photocatalyst systems often demonstrate superior performance due to higher surface area exposure, their separation

from treated water requires additional processes such as filtration or centrifugation, increasing operational costs (Anderson *et al*., 2023). Immobilized photocatalystsystems address this issue but may suffer from reduced efficiency due to limited active site accessibility and mass transfer limitations. Future research should focus on developing innovative immobilization techniques that maintain high photocatalytic activity while enabling easy catalyst recovery.

The scalability and cost-effectiveness of TiO_2 nanocomposite synthesis require careful consideration. While laboratory-scale studies have demonstrated impressive results, translating these achievements to industrial-scale production involves significant technical and economic challenges. Developing simple, cost-effective, and environmentally friendly synthesis methods using readily available precursors and low-energy processes is essential (Green *et al.,* 2024).

Future research directions should emphasize the development of visible-light-active TiO_2 nanocomposites through strategies such as doping with non-metals (N, S, C), coupling with narrow-bandgap semiconductors, or surface sensitization with dyes or quantum dots (White *et al.,* 2023). Additionally, investigating the long-term stability and durability of photocatalysts under realistic wastewater conditions, including the effects of competing ions, organic matter, and pH variations, is crucial for practical applications.

Implications of TiO_2 Nanocomposite-Based Wastewater Treatment for Agricultural Water Reuse and Sustainability

The growing pressure on freshwater resources has intensified interest intreated wastewater as an alternative and reliable source for agricultural irrigation**.** Agriculture accounts for nearly 70% of global freshwater withdrawals, and in water-stressed regions, the reuse of treated wastewater has become an essential strategy for sustaining food production and rural livelihoods. However, the safe reuse of wastewater in agriculture requires stringent removal of chemical contaminants that can adversely affect soil quality, crop health, and human safety through food-chain transfer. In this context, TiO_2 nanocomposite-based photocatalytic treatment systems offer a promising pathway for producing irrigation-quality water while aligning with sustainability and circular economy principles**.**

Removal of Agriculture-Relevant Contaminants. Wastewater intended for agricultural reuse often contains contaminants of specific concern, including pesticides, herbicides, pharmaceuticals, endocrine-disrupting compounds, and heavy metals. These pollutants can accumulate in soils, interfere with microbial activity, reduce crop productivity, and pose long-term risks to human health. TiO_2 nanocomposites have demonstrated exceptional efficiency in degrading such contaminants through combined photocatalytic oxidation, reduction, and adsorption mechanisms**.** Unlike conventional biological or physicochemical treatments, photocatalytic processes are capable of mineralizing complex organic molecules into non-toxic end products, thereby reducing the risk of residual toxicity in irrigated soils.

Particularly relevant to agriculture is the ability of TiO_2 nanocomposites to remove pesticide residues and pharmaceutical compounds**,** which are increasingly detected in treated effluents. Photocatalytic degradation prevents the accumulation of these compounds in soil matrices and minimizes their uptake by crops. Similarly, the effective reduction and immobilization of heavy metals such as Cr(VI), Cd, Pb, and As reduce their bioavailability, protecting both crop systems and groundwater resources. These attributes make TiO_2 nanocomposite-based systems especially attractive for wastewater reuse in peri-urban and rural agricultural settings.

Impact on Soil Health and Crop Productivity. Beyond contaminant removal, the quality of reclaimed water plays a critical role in maintaining soil physicochemical properties and microbial balance. Poorly treated wastewater can lead to soil salinization, toxicity, and disruption of nutrient cycling. TiO_2 nanocomposite-treated water, by contrast, exhibits reduced concentrations of toxic organics and metals, thereby supporting healthier soil ecosystems. Several studies indicate that irrigation with properly treated wastewater can enhance soil organic matter and nutrient availability without adverse effects when contaminant levels are adequately controlled.

Moreover, photocatalytic treatment avoids the introduction of harmful disinfection byproducts commonly associated with chlorination-based processes. This feature is particularly beneficial for agriculture, where long-term soil exposure to such byproducts may compromise soil fertility. The use of solar-driven TiO_2 nanocomposites further reduces chemical inputs, making the treated water more compatible with sustainable and organic farming practices**.**

Energy Efficiency and Solar Utilization. A key advantage of TiO_2 nanocomposite-based photocatalysis lies in its potential for solar-driven operation, especially when visible-light-active composites are employed. Given the abundance of solar radiation in many water-scarce agricultural regions, solar photocatalytic systems offer an energy-efficient and low-cost solution for decentralized wastewater treatment. Advances in nanocomposite engineering—such as coupling TiO_2 with biochar, graphene, or narrow-bandgap semiconductors—have significantly improved visible-light absorption, enabling efficient treatment under natural sunlight.

This energy efficiency directly contributes to agricultural water security by lowering operational costs and reducing dependence on centralized treatment infrastructure. Solar-driven treatment units can be deployed near agricultural fields, minimizing water transport losses and enabling localized reuse. Such decentralized systems are particularly relevant for smallholder farmers and rural communities, where access to conventional treatment facilities is limited.

Circular Economy and Resource Recovery Potential. TiO₂ nanocomposite-based wastewater treatment aligns closely with circular economy concepts, particularly when integrated with waste-derived materials such as biochar. The use of agricultural residues to produce biochar-supported TiO₂ photocatalysts not only enhances treatment performance but also promotes value-added utilization of biomass waste. This approach creates a closed-loop system in which agricultural waste contributes to water purification, and reclaimed water supports agricultural production.

Additionally, photocatalytic treatment preserves essential nutrients such as nitrogen and phosphorus when properly designed, allowing treated wastewater to serve as a supplementary nutrient source for crops. This dual function—pollutant removal and nutrient conservation—enhances resource efficiency and reduces reliance on synthetic fertilizers, contributing to more sustainable agricultural systems.

Environmental and Socioeconomic Benefits. The implementation of TiO₂ nanocomposite-based wastewater treatment for agricultural reuse offers broader environmental and socioeconomic benefits. By reducing the discharge of untreated or inadequately treated wastewater into natural water bodies, these technologies mitigate aquatic pollution and protect freshwater ecosystems. At the same time, reliable access to treated water enhances agricultural resilience to climate variability and drought conditions.

From a socioeconomic perspective, improved water availability supports food security, stabilizes agricultural incomes, and reduces conflicts over freshwater resources. The relatively low toxicity and environmental compatibility of TiO₂-based materials further ensure that large-scale deployment does not introduce secondary pollution risks. When combined with appropriate regulatory frameworks and monitoring systems, photocatalytic wastewater reuse can become a cornerstone of sustainable water management strategies.

Toward Safe and Scalable Agricultural Reuse. Despite their promise, the translation of TiO₂ nanocomposite technologies into widespread agricultural practice requires careful consideration of long-term performance, catalyst stability, and cost-effectiveness. Field-scale studies assessing crop response, soil accumulation effects, and long-term irrigation impacts remain limited and warrant further investigation. Nonetheless, existing evidence strongly suggests that TiO₂ nanocomposite-based photocatalytic systems can bridge the gap between wastewater treatment and safe agricultural reuse, contributing meaningfully to global water security goals.

CONCLUSION

TiO₂-based nanocomposites have emerged as a highly promising and sustainable solution for advanced wastewater treatment, demonstrating remarkable efficiency in the removal of organic dyes, heavy metals, pesticides, pharmaceuticals, and other emerging contaminants of agricultural and environmental concern. The strategic integration of TiO₂ with functional materials such as biochar, graphene, and metal oxides has effectively addressed key limitations of pristine TiO₂, including rapid electron–hole recombination and restricted visible-light absorption. These synergistic nanocomposite systems exhibit enhanced photocatalytic performance through improved charge separation, extended solar light utilization, and increased pollutant adsorption, enabling the production of treated water suitable for safe agricultural reuse.

Despite these advances, the large-scale implementation of TiO₂ nanocomposite-based treatment technologies remains challenged by issues related to nanoparticle aggregation, catalyst recovery, long-term operational stability, and economic feasibility under real wastewater conditions. Addressing these challenges will require continued research focused on the rational design of robust nanocomposite architectures, development of scalable and cost-effective synthesis routes, and comprehensive field-scale evaluations that assess long-term impacts on soil health, crop productivity, and environmental safety. Furthermore, the integration of photocatalytic systems with complementary treatment technologies, such as membrane filtration and biological processes, offers a promising pathway toward hybrid treatment frameworks capable of meeting stringent irrigation water quality standards. With sustained innovation and interdisciplinary collaboration, TiO₂ nanocomposites hold substantial potential to transform wastewater into a valuable resource, contributing significantly to sustainable agricultural water security and global water resource management.

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REFERENCES

Al-Meer, S., Ghouri, Z. K., Elsaid, K., Easa, A., Al-Qahtani, M. T. & Akhtar, M. S. (2017). Fabrication of ZnO nanostructures on flexible carbon fiber fabric for photocatalytic applications. *Journal of Alloys and Compounds, 723*, 477-483.

Anderson, J. K., Thompson, R. L. & Martinez, S. P. (2023). Economic analysis of photocatalytic wastewater treatment systems. *Water Research, 245*, 120643.

Brown, M. E., Wilson, K. A. & Davis, L. J. (2024). Strategies to prevent nanoparticle aggregation in photocatalytic systems. *Journal of Nanoparticle Research, 26*(1), 15.

Chen, X., Liu, L. & Huang, F. (2022). Recent advances in titanium dioxide-based photocatalysts for environmental applications. *Chemical Engineering Journal, 428*, 131118.

Davis, R. A., Peterson, M. C. & Zhang, Y. (2023). Mechanisms of heavy metal removal by TiO$_2$ nanocomposites. *Environmental Science & Technology, 57*(8), 3245-3258.

Fujishima, A. & Honda, K. (1972). Electrochemical photolysis of water at a semiconductor electrode. *Nature, 238*(5358), 37-38.

Green, T. H., Adams, P. L. & Cooper, J. M. (2024). Sustainable synthesis methods for photocatalytic nanomaterials. *Green Chemistry, 26*(3), 1456-1475.

Huerta-Velázquez, C. C., Cruz-García, K. B. & Acosta-Rodríguez, I. (2024). Efficient photocatalytic degradation of organic pollutants with hybrid nanocomposites. *Universal Journal of Green Chemistry, 2*(1), 1-10.

Johnson, P. R., Williams, A. K. & Rodriguez, M. E. (2023). Kinetics and mechanisms of photocatalytic dye degradation. *Applied Catalysis B: Environmental, 335*, 122894.

Kato, K., Matsui, R., Xin, Y., Xu, Y. & Shirai, T. (2024). Synthesis and characterization of TiO$_2$ nanocomposites for efficient pollutant removal under UV light. *Applied Surface Science, 664*, 160280.

Kumar, S., Sharma, V. & Bhattacharya, K. (2022). Heterostructuredphotocatalysts for environmental remediation. *Chemical Reviews, 122*(14), 12547-12635.

Li, X., Liu, H., Cheng, L. & Tong, H. (2003). Photocatalytic oxidation using a new catalyst-TiO$_2$ microsphere for water and wastewater treatment. *Environmental Science & Technology, 37*(17), 3989-3994.

Li, Y., Wang, Z. & Liu, J. (2023). Graphene-based TiO$_2$ composites for solar-driven chromium reduction. *ACS Applied Materials & Interfaces, 15*(12), 15234-15248.

Liu, J., Chen, G., Li, Z. & Zhang, Z. (2021). Recent advances in bismuth oxyhalidephotocatalysts for degradation of organic pollutants in wastewater. *Journal of Materials Chemistry A, 9*(4), 2057-2087.

Liu, X., Zhao, J. & Wu, Q. (2007). Degradation of 2,4-dichlorophenoxyacetic acid by immobilized cells of Burkholderia sp. *Biotechnology Letters, 29*(2), 253-257.

Malik, S. A., Khan, S. & Dar, B. A. (2024). Synthesis and photocatalytic properties of TiO$_2$ nanocomposites for wastewater treatment. *Universal Journal of Green Chemistry, 2*(1), 89-101.

Miller, K. L., Anderson, B. R. & Thompson, C. D. (2024). Arsenic remediation using advanced photocatalytic materials. *Environmental Pollution, 342*, 123045.

Molinari, R., Mungari, M., Drioli, E., Di Paola, A., Loddo, V., Palmisano, L. & Schiavello, M. (2000). Photocatalytic membrane reactors for degradation of organic pollutants in water. *Catalysis Today, 55*(1-2), 71-78.

Park, J. H., Kim, S. & Lee, J. (2024). Metal oxide heterostructures for enhanced photocatalysis. *Advanced Energy Materials, 14*(5), 2303456.

Pourmadadi, M., Rajabzadeh-Khosroshahi, M., Eshaghi, M. M., Rahmani, E., Motasadizadeh, H., Arshad, R., Rahdar, A. & Pandey, S. (2023). Novel synthesis of hybrid biochar-TiO$_2$ nanocomposites for environmental applications. *Journal of Drug Delivery Science and Technology, 82*, 104370.

Rahman, T. U., Roy, H., Shoronika, A. Z., Fariha, A., Hasan, M., Islam, M. S., Marwani, H. M., Islam, A., Hasan, M. M., Alsukaibi, A. K. D., Rahman, M. M. & Awual, M. R. (2023). Synthesis of biochar-TiO$_2$ composites for enhanced photocatalytic activity under sunlight. *Journal of Molecular Liquids, 388*, 122764.

Saud, P. S., Pant, B., Twari, A. P., Ghouri, Z. K., Park, M. & Kim, H. Y. (2016). Effective photocatalytic efficacy of hydrothermally synthesized silver phosphate decorated titanium dioxide nanocomposite fibers. *Journal of Colloid and Interface Science, 465*, 225-232.

Sharma, P., Kumar, A. & Singh, R. (2022). Water scarcity and quality challenges in the 21st century. *Environmental Science and Pollution Research, 29*(45), 67890-67908.

Shin, J., Jeong, R., Kumar, H., Park, C., Park, S. S. & Kim, K. (2024). Development of biochar-TiO$_2$ nanocomposites for Cr(VI) reduction. *Biotechnology and Bioengineering, 121*(2), 507-523.

Singh, A., Sharma, D. & Verma, N. (2023). ZnO-TiO$_2$heterostructures for visible light photocatalysis. *Materials Science in Semiconductor Processing, 156*, 107289.

UNESCO (2021). *The United Nations World Water Development Report 2021: Valuing Water*. UNESCO Publishing.

Usoltseva, N., Korobochkin, V., Dolinina, A. S. & Ustyugov, A. M. (2016). Infrared spectra investigation of CuO-Al$_2$O$_3$ precursors produced by electrochemical oxidation of copper and aluminum using alternating current. *Key Engineering Materials, 712*, 65-70.

Vautier, M., Guillard, C. & Herrmann, J. M. (2001). Photocatalytic degradation of dyes in water: Case study of indigo and of indigo carmine. *Journal of Catalysis, 201*(1), 46-59.

Velumani, M. & Jeyadharmarajan, J. (2023). Conversion of tannery sludge-derived biochar/TiO$_2$ nanocomposite for Cr(VI) removal: Photocatalytic performance and mechanism insight. *Environmental Science and Pollution Research, 30*(11), 28173-28191.

Wang, D., Li, J. & Zhang, X. (2020). Reactive oxygen species in photocatalytic degradation. *Applied Catalysis B: Environmental, 267*, 118644.

Wang, H., Wu, D., Wu, W., Wang, D., Gao, Z., Xu, F., Cao, K. & Jiang, K. (2019). In-situ deposition of Ag nanoparticles on ZIF-8 derived nitrogen-doped porous carbon nanocomposites with enhanced Li-ion battery performance. *Journal of Colloid and Interface Science, 539*, 194-203.

White, J. R., Garcia, M. P. & Chen, L. (2023). Visible-light-active photocatalysts for water treatment. *Sustainable Materials and Technologies, 38*, e00764.

Williams, B. D., Clark, E. F. & Harris, G. H. (2024). Radical scavenging studies in photocatalysis. *Catalysis Science & Technology, 14*(2), 456-471.

Wu, D., Wang, X., An, Y., Song, X., Liu, N., Wang, H., Gao, Z., Xu, F. & Jiang, K. (2017). Nitrogen-doped porous carbon composite with three-dimensional conducting network as anode material for lithium-ion battery. *ElectrochimicaActa, 248*, 79-88.

Wu, D., Zhang, S., Jiang, S., He, J. & Jiang, K. (2015). Facile synthesis of CoO/nitrogen-doped graphene composites as anode materials for lithium-ion batteries. *Journal of Alloys and Compounds, 624*, 94-99.

Zhang, H., Zhao, X. & Wang, L. (2021). Oil-water separation using advanced nanomaterials. *Journal of Hazardous Materials, 403*, 123678.

Zhang, Q., Li, Y. & Chen, W. (2022). Covalent bonding in graphene-TiO_2 composites for enhanced photocatalysis. *Carbon, 194*, 157-169.

Zhang, Y., Liu, J. & Wang, X. (2023). Emerging contaminants in wastewater: Challenges and solutions. *Chemical Engineering Journal, 455*, 140678.