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Recent Progress in Wastewater Treatment: Exploring the Roles of Zero-Valent Iron and Titanium Dioxide Nanoparticles

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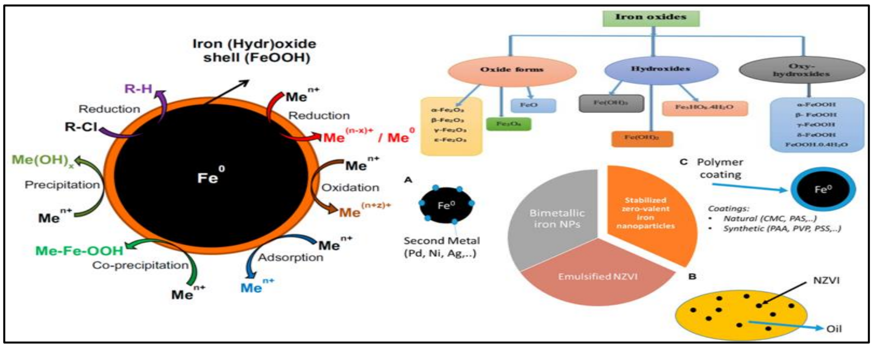
ABSTRACT

Significant environmental issues have been created by the growing outflow of urban and industrial wastewater, which calls for the development of sophisticated and effective treatment systems. Zero-valent iron (ZVI) and titanium dioxide (TiO_2) nanoparticles have become well-known among developing solutions because of their exceptional reactivity, affordability, and potential for large-scale applications. With an emphasis on their processes, efficacy, and difficulties, this paper examines the most recent developments in the application of ZVI and TiO_2 nanoparticles for wastewater treatment. TiO_2 nanoparticles have remarkable photocatalytic qualities, efficiently breaking down persistent organic pollutants under UV and visible light, whereas ZVI nanoparticles have high reductive capabilities, allowing the removal of heavy metals, chlorinated compounds, and organic pollutants. Their efficiency, stability, and reusability have been improved by recent alterations such as doping, surface functionalization, and hybrid nanocomposites. However, obstacles to wider use include recovery issues, possible ecotoxicity, and nanoparticle aggregation. To increase the sustainability and viability of ZVI and TiO_2 applications, this study also covers cutting-edge techniques, including magnetic separation, green synthesis, and integration with other treatment methods. Future studies should concentrate on creating scalable treatment plans, assessing long-term environmental effects, and improving nanoparticle design. ZVI and TiO_2 nanoparticles have enormous potential to transform wastewater treatment and support global water sustainability by solving these issues.

Graphical Abstract



INTRODUCTION

Rapid urbanization, industry, population increase, and insufficient infrastructure all contribute to the complicated and growing global wastewater environment (Tariq et al., 2023). Effective wastewater management is becoming more and more important as freshwater supplies are depleting due to misuse and climate change. More than 80% of wastewater worldwide is being released into the environment untreated, endangering ecosystems, biodiversity, and public health (Jan et al., 2022). Because they have less access to contemporary sanitary facilities and wastewater treatment systems, developing nations are more vulnerable. While the lack of centralized systems in rural areas frequently results in the direct dumping of sewage into rivers, lakes, and groundwater sources, outdated infrastructure in metropolitan areas makes it difficult to keep up with the growing demand (Capodaglio et al., 2017). Water contamination is made worse by industrial effluents that contain persistent organic pollutants, hazardous heavy metals, and new contaminants, including microplastics and medications. Through nitrogen and phosphorus-rich runoff, the agricultural sector adds to nutrient loading, which causes eutrophication and the growth of toxic algal blooms (Khan et al., 2014). Furthermore, wastewater is a potential source of public health data, which has been highlighted by the COVID-19 pandemic, underscoring the need for wastewater surveillance. Innovative approaches, including decentralized treatment systems, wastewater recycling, nature-based solutions, and the circular economy model, provide encouraging avenues for sustainable wastewater management despite the bleak future. To overcome these complex issues and ensure water security for future generations, international cooperation, legislative change, technical advancement, and public awareness are crucial (Mishra et al., 2021).

One of the most important environmental issues of the twenty-first century, ensuring clean and safe water, is being addressed in a revolutionary way with the advent of nanotechnology in water treatment (Aithal et al., 2022). While somewhat successful, traditional water treatment techniques frequently fail to remove new pollutants, including pesticides, heavy metals, medicines, and microplastics, which, even at low levels, can have serious negative effects on the environment and human health. By using engineered nanomaterials with exceptional surface area, reactivity, and selectivity, such as carbon nanotubes, graphene oxide, metal-organic frameworks (MOFs), zero-valent iron nanoparticles, and titanium dioxide (TiO_2) nanostructures, nanotechnology provides a promising substitute (Sahoo et al., 2020). With impressive effectiveness, these materials have been used to improve filtration, disinfection, catalysis, and adsorption processes. For example, photocatalytic nanomaterials such as TiO_2 may use sunlight to break down organic contaminants through sophisticated oxidation processes, whereas zero-valent iron nanoparticles have shown great efficacy in breaking down chlorinated organic compounds (Li et al., 2021). Additionally, nanotechnology makes it possible to create multipurpose hybrid systems that provide real-time monitoring and treatment by combining sensing, capturing, and detoxifying capabilities on a single platform. Notwithstanding these developments, scalability, affordability, environmental safety, and legal frameworks remain obstacles to the broad use of nanotechnology in water cleanup (Dada et al., 2024). The necessity for thorough life-cycle evaluations and eco-toxicological research is highlighted by worries about the toxicity and persistence of nanomaterials in aquatic environments. However, there is hope for overcoming these obstacles via ongoing research and development in biodegradable nanomaterials, green synthesis techniques, and nanocomposite technology (Ahmed et al., 2022). Nanotechnology is emerging as a key frontier in the development of sustainable, effective, and adaptable water purification systems, not simply as a technique, as global pollution and water scarcity worsen (Adesina et al., 2024).

The comparative analysis of titanium dioxide (TiO_2) and zero-valent iron (ZVI) as advanced materials in environmental remediation reveals each material's advantages, special workings, and expanding significance in the face of rising pollution and industrial waste issues (Feisal et al., 2024). The purpose of this study is to evaluate and compare the physicochemical characteristics, reactivity profiles, environmental suitability, and potential for synergy between ZVI and TiO_2 in the degradation of contaminants. ZVI has drawn interest because of its affordability, potent reductive properties, and efficiency in eliminating a variety of pollutants, including heavy metals and chlorinated organics (Yan et al., 2024). Its effectiveness in in-situ groundwater remediation is widely known, and it provides long-term, sustainable solutions for managing contamination. On the other hand, TiO_2 is particularly promising for wastewater treatment and air purification due to its exceptional photocatalytic qualities, chemical stability, and capacity to break down a wide range of organic contaminants when exposed to UV or solar radiation (Pham et al., 2021). Although each material has unique benefits, their hybrid or mixed applications are becoming a new frontier because they provide improved degradation kinetics, broader operating conditions, and the ability to treat several contaminants (Ahmed et al., 2021). This review is novel because it takes an integrative approach, examining ZVI and TiO_2 side by side as well as their possible convergence in hybrid systems, recent developments in material modifications, and their applicability to upcoming industrial and environmental applications. For researchers, environmental engineers, and policymakers interested in utilizing the full potential of these materials for global environmental challenges, this review offers a timely and thorough overview by placing the discussion within the larger framework of green chemistry and sustainable remediation. This study aims to give a thorough summary of current developments in the use of titanium dioxide (TiO_2) and zero-valent iron (ZVI) nanoparticles in wastewater treatment. To identify current trends, research gaps, and future objectives for improving nanoparticle-based remediation technologies, this article objectively assesses their effectiveness, modes of action, comparative benefits, and limits in eliminating various contaminants.

Synthesis and Surface Engineering

In the production and surface engineering of nanomaterials, green and waste-derived synthesis techniques have become essential tactics, providing sustainable, economical, and ecologically acceptable substitutes for traditional chemical synthesis procedures (Abdelbasir et al., 2020). These methods create nanoparticles with less harm to the environment by using natural precursors, including plant extracts, agricultural waste, and industrial waste streams. In addition to lowering metal ions, the phytochemicals found in green sources also serve as organic stabilizing and capping agents, producing materials with improved biocompatibility and decreased toxicity. Additionally, by turning garbage into valuable nanostructures, waste-derived pathways support circular economy models. Following synthesis, these nanomaterials are further modified using nano-structuring methods intended to boost their reactivity and surface area. The surface-to-volume ratio is greatly increased by techniques including templating, etching, and the creation of porous, hierarchical, or core-shell structures (Sun et al., 2015). This is important for applications in drug delivery, environmental cleanup, catalysis, and sensing. To modify the physicochemical characteristics of these nanostructures, surface functionalization is essential. Researchers can adjust the stability, solubility, targeting capability, and interaction of nanomaterials with biological or environmental interfaces by adding polymers, bio-ligands, or metallic coatings. Metal functionalization can provide further catalytic, magnetic, or optical capabilities, bio-ligands enable selectivity in targeting cells or pollutants, and polymers give a versatile platform for drug loading and sustained release. Thus, combining green synthesis with sophisticated surface engineering is a revolutionary method for creating multipurpose nanomaterials that are propelling advancements in medicinal applications about energy and the environment (Samuel et al., 2022).

Mechanisms of Action

In advanced oxidation processes (AOPs) for environmental remediation, understanding the mechanisms of action is crucial to optimizing pollutant degradation efficiency (Saravanan et al., 2022). Zero-valent iron (ZVI) and titanium dioxide (TiO_2) represent two widely studied materials due to their distinct yet complementary oxidative mechanisms. ZVI primarily facilitates contaminant breakdown through electron transfer processes. In aqueous environments, ZVI undergoes corrosion, releasing Fe^{2+} ions and electrons that participate in reductive and oxidative transformations. These electrons can reduce contaminants directly or generate reactive species, such as hydroxyl radicals (•OH), via Fenton-like reactions. In contrast, TiO_2 acts through photocatalysis, where ultraviolet (UV) light excites the semiconductor, promoting electrons from the valence band to the conduction band and leaving behind positively charged holes. The production of reactive oxygen species (ROS), such as •OH and superoxide anions ($•O_2^-$), which oxidize organic contaminants non-selectively, is fueled by these photogenerated electron-hole pairs. Hybrid systems that combine these processes, such as TiO_2-ZVI, have been the focus of recent research. By functioning as an electron sink, the ZVI component in these composites improves the separation of photogenerated electron-hole pairs, increasing the production of reactive oxygen species and extending their lifespan (Li et al., 2021). Additionally, the hybrid structure allows for simultaneous oxidation and reduction at several active sites, which improves thermodynamic feasibility and speeds up degradation rates. Significant benefits are provided by these dual-action routes in terms of response speeds, mineralization effectiveness, and environmental flexibility. When both oxidative and reductive processes are present, pseudo-first-order degradation models with lower activation energies are frequently produced, suggesting increased reactivity from a kinetic perspective. These hybrid systems are very effective and show promise for treating stubborn contaminants in water and wastewater matrices because the thermodynamic connection of ZVI and TiO_2 significantly reduces energy barriers for intermediate reactions (Ali et al., 2024).

Applications in Wastewater Remediation

In wastewater remediation, the use of cutting-edge materials and technologies has greatly advanced, providing promising means of effectively eliminating a variety of contaminants, such as organics, heavy metals, toxic inorganics, micropollutants, and endocrine-disrupting substances (Sharma et al., 2024). Because of their toxicity, durability, and propensity for bioaccumulation, organic pollutants, including dyes, pesticides, and medications, are frequently detected in both residential and commercial wastewater and represent a major risk to aquatic ecosystems and human health. Advanced oxidation processes (AOPs) and adsorption employing metal-organic frameworks (MOFs), activated carbon, and biochar have proven to be highly effective in breaking down or eliminating these organic compounds. Because it can mineralize complicated organics into innocuous end products, photocatalysis employing nanomaterials like TiO_2 and

ZnO under visible or UV light is becoming more and more popular. At the same time, because heavy metals and toxic inorganics like arsenic (As), lead (Pb), and chromium (Cr) are not biodegradable and can cause long-term pollution, their cleanup is still a major concern (Rahman et al., 2019). Excellent selectivity and binding capacity for these metals have been demonstrated by novel materials such as magnetic nanoparticles, functionalized graphene oxide, and biosorbents made from agricultural waste. Furthermore, the development of more sensitive and effective removal methods has been made necessary by the proliferation of micropollutants, including endocrine-disrupting chemicals (EDCs) such as synthetic hormones, triclosan, and bisphenol A. The complicated and low-concentration character of EDCs may be addressed in a variety of ways by combining membrane filtration methods (such as reverse osmosis and nanofiltration) with hybrid systems like membrane bioreactors (MBRs) and enzyme-based degradation systems. For complete pollutant removal and environmental safety, these new methods must be included in traditional wastewater treatment systems. Cost-effective, scalable, and environmentally friendly remediation techniques that can be tailored to different wastewater compositions and treatment objectives are becoming more and more important as research progresses (Ejairu et al., 2024).

Emerging and Underexplored Applications

With new and untested applications that have the potential to revolutionize the way we manage sustainability and global health issues, the field of environmental biotechnology and nanotechnology is developing quickly (Prajapati et al., 2024). The identification and management of mobile genetic elements (MGEs) and antibiotic resistance genes (ARGs), which play a crucial role in the spread of antibiotic resistance throughout ecosystems, is one such exciting field. The simplicity, quick reaction, and field-deployability of innovative systems that combine colorimetric detection and remediation in a single step are drawing interest. These platforms actively neutralize toxins while providing real-time information. The effectiveness of environmental cleanup plans and monitoring programs is greatly increased by this dual functionality. Meanwhile, the accuracy of environmental interventions is being redefined by intelligent and programmable nanoparticles. Targeted distribution, controlled release, and context-sensitive remedial operations that reduce off-target impacts and ecological damage are made possible by the ability to construct these nanosystems to react to certain biological or chemical stimuli. Simultaneously, bioinspired surface engineering is using natural principles, such as lotus leaf microstructures or shark skin, to create surfaces that are resistant to microbial colonization and biofilm formation without the use of harmful biocides, especially in the creation of anti-fouling systems (Liu et al., 2024). This method adheres to sustainable design principles while also extending the lifespan and usefulness of medical and maritime equipment. Furthermore, a novel paradigm where waste degradation results in the creation of clean energy is introduced by combining photocatalytic hydrogen production with environmental restoration. Through the use of sunlight to propel the evolution of hydrogen and the breakdown of pollutants, scientists are developing circular systems that transform environmental liabilities into lucrative assets. These new developments highlight a move toward multipurpose, environmentally friendly, and precision-driven technologies that not only lessen current environmental issues but also create new opportunities for ecological balance and resource recovery (Zaid et al., 2024).

Table 1

Emerging and Underexplored Applications in Environmental Nanotechnology

Application Area	Concept Overview	Innovative Mechanism	Advantages	Challenges & Limitations	Future Perspectives
Antibiotic Resistance Genes (ARGs) & Mobile Genetic Elements (MGEs)	Targeting ARGs and MGEs that contribute to environmental antibiotic resistance spread.	Gene-targeting strategies (e.g., CRISPR-Cas), integron inhibitors, and phage therapy.	Potential to reduce horizontal gene transfer and environmental contamination.	Difficulty in tracking gene transfer routes; biosafety and ethical issues.	Genomic surveillance networks and AI-assisted prediction tools for risk mitigation.
Colorimetric Detection + Remediation in a Single Step	One-pot systems that allow detection of ARGs or contaminants and simultaneously trigger degradation or removal.	Use of chromogenic substrates linked to enzymatic bioremediation or nanoparticle response.	Low-cost, rapid diagnostics with actionable remediation; portable and field-deployable.	Sensitivity can be affected by matrix complexity; limited commercial scaling.	Development of multiplex sensors and integration with IoT-based environmental monitoring.
Smart and Programmable Nanoparticles for Precision Control	Responsive nanostructures that change behavior upon environmental stimuli or molecular recognition.	DNA/RNA aptamer-guided targeting, pH-responsive drug release, photoresponsive systems.	High specificity, reduced off-target effects, and enhanced efficacy in complex environments.	High production cost, regulatory hurdles, and long-term ecological effects.	Integration with biosensing platforms and AI-guided nano-systems for

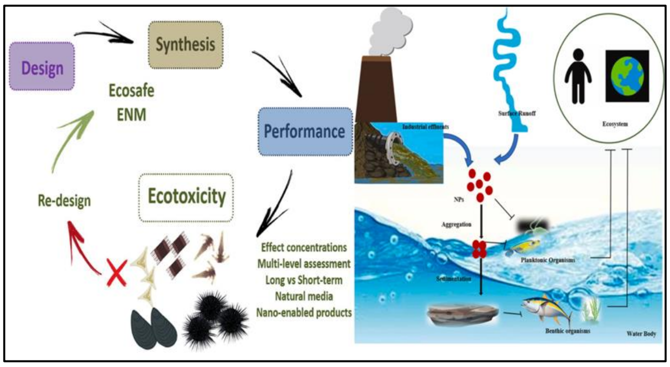
					intelligent remediation.
Bioinspired Surface Engineering for Anti-Fouling Systems	Mimicking natural anti-fouling surfaces (e.g., lotus leaf, shark skin) to resist biofilm formation and ARG spread.	Micro/nanotexturing, zwitterionic and superhydrophobic coatings, dynamic liquid interfaces.	Non-toxic, durable, and passive antifouling without chemical leaching.	Scalability to large surfaces; long-term stability in harsh environments.	3D-printed surface designs and stimuli-responsive dynamic surfaces for smart control.
Photocatalytic Hydrogen Production as a Value-Added Co-Product	Harnessing solar energy for simultaneous ARG degradation and clean energy production.	Use of doped TiO_2, g-C_3N_4, or bismuth-based photocatalysts for dual function.	Energy-efficient process, dual benefit of decontamination and green hydrogen fuel.	Low quantum efficiency; competing reactions, catalyst deactivation.	Advanced heterojunctions, co-catalysts, and visible-light-responsive materials to boost performance.

Nano–Bio–Eco Interactions

A multifaceted view of how engineered nanomaterials (ENMs) interact with biological systems and the wider environment is provided by the study of nano-bio-eco interactions, which highlights the pressing need to assess the long-term destiny and ecological effects of ENMs (Ashraf et al., 2021). Concern over the possibility of environmental toxicity from nanoparticle (NP) discharge is developing as nanotechnology is more incorporated into industrial, medicinal, and environmental applications. Nanoparticles can interact with a variety of biological organisms in aquatic environments, such as fish, zooplankton, algae, and microbial communities. This interaction frequently results in abnormalities in physiological, reproductive, and behavioral processes. The aggregation, dissolution, and bioavailability of nanoparticles in complex environmental matrices are impacted by their composition, size, surface charge, and coating. By changing microbial diversity and metabolic activity, nanoparticles can disrupt ecosystem functions, including organic matter decomposition and nutrient cycling. Specifically, even at low concentrations, silver, titanium dioxide, and zinc oxide nanoparticles have shown toxicity to aquatic animals and beneficial microbial communities. The creation of biodegradable or environmentally friendly nanomaterials with lower toxicity and persistence is becoming more and more important in response to these ecological threats (Vurro et al., 2019). Frequently made from biocompatible and sustainable resources, these green-engineered nanoparticles have specific surface changes that improve degradability and reduce bioaccumulation. This move toward sustainable nanotechnology supports a lifecycle-based strategy that takes into account the full journey of nanoparticles from manufacture to environmental absorption, which is consistent with the ideas of green chemistry and the circular economy. To forecast the behavior of nanoparticles in practical situations and create materials that balance technological innovation with ecological resilience, future research must use multidisciplinary methods from environmental chemistry, systems biology, and nanotoxicology (Isibor et al., 2024).

Figure 1

Nano–Bio–Eco Interactions



Integration with Modern Tech

The deployment and operational efficiency of advanced water treatment systems, especially those that use nanoscale zero-valent iron (ZVI) and titanium dioxide (TiO_2) composites, are being revolutionized by the integration of contemporary technologies like artificial intelligence (AI), the Internet of Things (IoT), and remote sensing (Kumar et al., 2023). These systems can adapt to changing pollutant levels, maximize treatment efficiency, and reduce energy usage under dynamic environmental settings by integrating AI-driven prediction algorithms and real-time monitoring sensors. Coordinated water quality management in rural or underserved areas is made possible by IoT connection, which enables dispersed treatment modules to communicate with central data centers. Specifically, the creation of modular ZVI/TiO_2 reactors presents a revolutionary method for point-of-use and off-grid applications. Situations. Additionally, the development of 3D-printed composite filters that incorporate nanomaterials like graphene oxide, ZVI, and TiO_2 improves material efficiency and structural accuracy. Heavy metals, viruses, and organic pollutants may be precisely and effectively removed using these printed filters, which can be tailored for site-specific contaminants (Baig et al., 2024). They are perfect for portable or emergency water treatment situations because of their lightweight design and simplicity of construction. All things considered, the combination of nanotechnology and contemporary technology infrastructure has enormous potential for developing intelligent, robust, and sustainable water purification systems that are suited to the problems of the twenty-first century (Gleick et al., 2000).

Nanomaterial Microtargeting in Multicomponent Wastewater

A state-of-the-art method for accomplishing precise remediation in complicated industrial effluents, where many pollutants like dyes, nitrates, and heavy metals coexist and interact, is nanomaterial microtargeting in multicomponent wastewater treatment (Verma et al., 2024). One of the most promising approaches is the removal of pollutants using ligand-functionalized zero-valent iron (ZVI) and titanium dioxide (TiO_2) nanocomposites, which provide a highly selective and cooperative mechanism. Because TiO_2 nanoparticles may produce reactive oxygen species when exposed to UV or visible light, they are widely recognized for their potent photocatalytic activity and affinity for organic contaminants, particularly dye molecules. Because of this, TiO_2 is very good at breaking down aromatic dye complexes that are frequently present in effluent from the textile and pharmaceutical industries. However, because of its strong reductive potential, ZVI can be used to target inorganic pollutants. Such as heavy metal ions like lead, cadmium, and arsenic, chromates, and nitrates. Researchers can improve binding effectiveness and reaction kinetics by functionalizing the surfaces of these nanomaterials with certain ligands, such as amines, carboxyl groups, or thiols, which will fine-tune their selectivity toward target pollutant classes. For example, amine-modified TiO_2 may enhance electrostatic interactions with anionic dye species, whereas thiol-functionalized ZVI can preferentially bind to soft metal ions such as cadmium or mercury (Ahmaruzzaman et al., 2019). By enabling pollutant-specific interactions, reducing cross-reactivity, and improving overall treatment efficacy, these functionalized nanomaterials provide a microtargeting platform that addresses the heterogeneity of industrial wastewater when combined in a hybrid matrix or applied successively in treatment stages. Furthermore, this approach is positioned as a scalable and sustainable option for next-generation wastewater treatment systems due to the flexibility of ligand attachment and the possibility of catalyst renewal (Faheem et al., 2024).

Table 2

Nanomaterial Microtargeting in Multicomponent Wastewater

Nanomaterial System	Functionalization	Target Pollutant Class	Pollutant Examples	Mechanism	Key Advantage
TiO_2 nanoparticles	Surface-treated	Organic Dyes	Methylene Blue, Rhodamine B	Photocatalytic oxidation	High affinity for chromophores
TiO_2 nanoparticles	Amino-silane	Reactive Dyes (anionic)	Reactive Black 5, Congo Red	Electrostatic + photocatalysis	Strong anionic dye binding
TiO_2@Ag nanocom posite	Silver nanoparticle coating	Dyes & Microbes	Mixed effluent (bacterial + dye)	Dual action: photocatalysis & antimicrobial	Broad-spectrum targeting
Nanoscale ZVI	EDTA-functionalized	Heavy Metals	Pb^{2+}, Cr^{6+}, Cd^{2+}	Chelation + reduction	Selective metal capture
ZVI nanoparticles	Thiol ligands	Soft Metals	Hg^{2+}, As^{3+}	Sulfur-metal bonding	High selectivity for soft ions
ZVI@TiO_2 (core–shell)	(core–shell) Ligand-free	Mixed Metals & Dyes	Cd^{2+} + Methylene Blue	Simultaneous reduction & oxidation	Broad-spectrum synergy
Magnetic ZVI@TiO_2	Carboxylic acids	Nitrates & Nitrites	NO_3^-, NO_2^-	Reductive denitrification	Stability & selectivity
ZVI@TiO_2 with Imidazole	Imidazole groups	Drugs & Surfactants	Tetracycline, QACs	Redox + H-bonding	Targets metal-like and organic ions
ZVI–TiO_2/GO hybrid	Graphene oxide	VOCs	Phenol, Toluene	Adsorption + AOP	Enhanced surface & conductivity
Mesoporous TiO_2–Fe	Phosphonate ligands	Phosphates	PO_4^{3-}, Glyphosate	Complexation + photo catalysis	Specific to organophosphates
ZVI–TiO_2–Biochar	Carboxyl/Phenolic groups	Textile Wastewater	Dyes, metals, solvents	Adsorption + photocatalysis	Eco-friendly & sustainable
Chitosan–ZVI–TiO_2	Chitosan amino groups	Pharmaceuticals (PPCPs)	Diclofenac, Sulfamethoxazole	Adsorption + sustained release	Biopolymer-assisted delivery
ZVI@TiO_2	Ligand-free	Mixed Industrial Waste	Multiple pollutant types	Integrated redox–photo action	Versatile multifunctionality
TiO_2–CNT hybrid	Non-functionalized	Dyes & VOCs	Reactive Blue 19, Benzene	Photocatalysis + π–π stacking	High dye & aromatic pollutant removal

Challenges and Limitations

Although the use of nanoparticles, especially TiO_2-based nanomaterials, in water purification and environmental remediation has enormous promise, several important obstacles and restrictions prevent their widespread use (Devarajan et al., 2025). Aggregation of nanoparticles, a phenomena in which individual particles group together to reduce surface area and, as a result, photocatalytic efficacy, is one of the main issues. In natural or wastewater settings, where clustering is encouraged by high ionic strengths and organic debris, this aggregation is frequently made worse. Catalytic activity is also gradually decreased by passivation, which is the deactivation of the nanoparticle surface brought on by extended contact to pollutants or environmental factors. Limitations in light penetration, particularly for TiO_2 photocatalysts that need UV light to activate, exacerbate these material-level difficulties. Light absorption and scattering significantly decrease the penetration depth in murky or turbid waters, restricting the photocatalytic zone and reducing overall efficiency. Another technological barrier is the recovery and recyclability of nanoparticles; existing techniques for removing nanoparticles from treated water are either ineffective, expensive, or lacking, which raises questions about possible environmental hazards and secondary contamination (Saleh et al., 2024). Furthermore, the scalability and economic viability of such technologies in large-scale or low-resource contexts are called into question because of the high production costs and technological complexity involved in the synthesis and deployment of nanoparticles. Finally, safety assessments and regulatory frameworks have not kept up with the quick development of nanotechnology. The long-term environmental destiny, toxicity, and bioaccumulation of manufactured nanoparticles are still poorly understood, which makes it difficult for regulators to approve them and for the general public to accept them. To facilitate the safe and efficient use of nanoparticles in environmental applications, these combined limits underscore the necessity of ongoing multidisciplinary research centered on material innovation, process optimization, risk assessment, and policy development (Keshavan et al., 2024).

Future Directions and Innovations

Innovations at the nexus of artificial intelligence (AI), sustainability, and hybrid material engineering are driving future directions in the creation of functional nanomaterials for industrial and environmental applications (Konstantopoulos et al., 2022). AI-driven design and discovery of functional nanomaterials is one of the most revolutionary developments. Machine learning algorithms anticipate structure-property connections, optimize synthetic approaches, and hasten the creation of highly selective, multifunctional materials. When it comes to customizing nanomaterials for energy conversion, pollution removal, and catalysis, this computational method is proving very effective. Concurrently, the development of next-generation hybrid nanomaterials, like metal-organic frameworks (MOFs) and graphene-TiO_2-ZVI (zero-valent iron) composites, is expanding the capabilities of materials by providing improved surface reactivity, stability, and adjustable porosity for use in gas separation, water purification, and photocatalysis. Furthermore, using circular economy techniques, most notably employing nanomaterials to recover precious metals from industrial wastewater, offers a long-term solution to resource shortages and waste management. These technologies lessen the environmental impact in addition to facilitating the capture and reuse of metals (Izatt et al., 2014). To provide robustness and consistency in real-world applications, future research is also anticipated to focus on climate-responsive systems that operate effectively in a variety of environmental situations, such as low-light or low-temperature scenarios. Combining enzymatic biocatalysis with nanomaterials to create bio-nano hybrid systems that make use of both the stability of nanoparticles and the specificity of enzymes for accurate and effective environmental cleanup is equally promising. Lastly, self-powered remediation systems are a step toward decentralized, low-energy treatment options, especially those that combine solar and microbiological energy sources. These solar-microbial synergies support worldwide initiatives for green energy and self-sufficient environmental technology by using ambient light and microbial metabolism to drive pollutant degradation. When taken as a whole, these paths show a vibrant and multidisciplinary field that blends artificial intelligence, nanotechnology, biology, and sustainability to transform the way materials are developed and used for industrial and environmental effects (Tawfik et al., 2024).

Comparative Analysis

In the world of sophisticated oxidation processes and water purification technologies, Zero-Valent Iron (ZVI) and Titanium Dioxide (TiO_2) stand out as two significant materials exploited for pollutant remediation owing to their different physicochemical features and catalytic efficiency (Petala et al., 2016). These materials differ significantly in some important operating areas when compared. Widely known for its exceptional UV photocatalytic activity, TiO_2 exhibits greater removal efficiency for a variety of organic contaminants, particularly when exposed to regulated light and at ideal pH levels (usually acidic to neutral). On the other hand, ZVI is excellent at reducing heavy metals and chlorinated compounds, demonstrating strong performance even in anoxic or darker settings where photonic activation is not required. Operationally, TiO_2 needs certain light sources, mainly UV-A or visible light-activated doped varieties, which might increase energy requirements. Although ZVI is more adaptable in ambient circumstances, it frequently needs constant reactivity and is susceptible to passivation and aggregation problems, which might lower its long-term efficacy. Due to specific lighting and reactor design, TiO_2 systems often need larger initial investments in terms of lifecycle cost and energy demands; nevertheless, they provide long-term stability with low regeneration requirements. On the other hand, ZVI offers an upfront cost-effective option, especially in poor nations, but its continuous operating load is exacerbated by the need to replenish materials regularly and the possibility of disposing of iron sludge. The strategic placement of each item is further clarified by a SWOT matrix analysis: ZVI's simplicity, affordability, and ability to reduce are its main advantages (Nguyen et al., 2023). ZVI has the potential to enhance reactivity through nanostructuring or integration with other treatment methods. Conversely, the main drawbacks of TiO_2 are its high energy requirements and restricted capacity to absorb solar light, while its virtues include great oxidative potential and long-term stability. Threats to TiO_2 include scaling problems and safety concerns with nanoparticles, while opportunities center on doping with metals or non-metals to improve visible light responsiveness. These observations together guide future studies and real-world applications, highlighting the need for application-specific considerations when choosing between ZVI and TiO_2, taking desired pollutant profiles, cost, and environmental factors into account (Beavers et al., 2024).

CONCLUSION

This analysis concludes by highlighting the revolutionary potential of nanotechnology in a variety of fields and providing deep insights into its uses, difficulties, and prospective directions. According to the synthesis of recent research, nanomaterials have special physicochemical characteristics, including high surface area-to-volume ratios, tunable functionalities, and increased reactivity, which make them essential tools for tackling contemporary issues like smart materials, renewable energy systems, targeted drug delivery, and environmental remediation. But these developments also bring up serious issues with toxicity, long-term environmental effects, and moral application. A coordinated, multidisciplinary approach is therefore crucial. To better comprehend their environmental footprints, researchers are urged to concentrate on creating biocompatible, environmentally friendly nanomaterials through the use of green synthesis techniques and lifespan evaluations. Policymakers must create precise, scientifically based regulatory frameworks with precise rules for the use, disposal, and monitoring of nanoparticles that guarantee safety without impeding innovation. However, to ensure responsible manufacture and deployment, engineers should give priority to incorporating sustainability concepts into the design and scaling up of nanotechnologies. To turn laboratory discoveries into practical solutions, strong partnerships between scientists, engineers, regulators, and industry stakeholders are essential. In the end, nanotechnology's future depends not only on its technological development but also on its capacity to support the more general objectives of ethics, sustainability, and social benefit; hence, multidisciplinary cooperation is essential to its responsible development.

REFERENCES

Abdelbasir, S. M., McCourt, K. M., Lee, C. M., & Vanegas, D. C. (2020). Waste-derived nanoparticles: Synthesis approaches, environmental applications, and sustainability considerations. *Frontiers in Chemistry*, *8*. https://doi.org/10.3389/fchem.2020.00782

Adesina, O. B., William, C., & Oke, E. I. (2024). Evolution in water treatment: Exploring traditional self-purification methods and emerging technologies for drinking water and wastewater treatment: A review. *World News of Natural Sciences*, *53*, 169-185. http://psjd.icm.edu.pl/psjd/element/bwmeta1.element.psjd-d40756fc-6312-4e98-bc2e-813aa6f447fe

Ahmaruzzaman, M. (2019). Nano-materials: Novel and promising adsorbents for water treatment. *Asian Journal of Water, Environment and Pollution*, *16*(3), 43-53. https://doi.org/10.3233/ajw190032

Ahmed, S. F., Mofijur, M., Rafa, N., Chowdhury, A. T., Chowdhury, S., Nahrin, M., Islam, A. S., & Ong, H. C. (2022). Green approaches in synthesising nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges. *Environmental Research*, *204*, 111967. https://doi.org/10.1016/j.envres.2021.111967

Ahmed, S., Mofijur, M., Nuzhat, S., Chowdhury, A. T., Rafa, N., Uddin, M. A., Inayat, A., Mahlia, T., Ong, H. C., Chia, W. Y., & Show, P. L. (2021). Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater. *Journal of Hazardous Materials*, *416*, 125912. https://doi.org/10.1016/j.jhazmat.2021.125912

Aithal, P. S., & Aithal, S. (2022). Opportunities and challenges for green and eco-friendly nanotechnology in twenty-first century. *Sustainable Nanotechnology*, 31-50. https://doi.org/10.1002/9781119650294.ch3

Ali, S., Badar, M. S., Daniyal, Nikkhah, A., Fen, C. S., Nouri, A., Mohammad, A. W., Lun, A. W., Nourigheimasi, F., Ng, L. Y., & Mahmoudi, E. (2024). Progress in nanomaterial-driven redox reactions for water purification: A critical review. *Desalination and Water Treatment*, *320*, 100616. https://doi.org/10.1016/j.dwt.2024.100616

Ashraf, S. A., Siddiqui, A. J., Elkhalifa, A. E., Khan, M. I., Patel, M., Alreshidi, M., Moin, A., Singh, R., Snoussi, M., & Adnan, M. (2021). Innovations in nanoscience for the sustainable development of food and agriculture with implications on health and environment. *Science of The Total Environment*, *768*, 144990. https://doi.org/10.1016/j.scitotenv.2021.144990

Baig, A., Sial, S. A., Qasim, M., Ghaffar, A., Ullah, Q., Haider, S., Fatima, S., Shawal, L., & Ather, N. (2024). Harmful health impacts of heavy metals and behavioral changes in humans. *Indonesian Journal of Agriculture and Environmental Analytics*, *3*(2), 77-90. https://doi.org/10.55927/ijaea.v3i2.10431

Beavers, J. (2024). *Development of Novel Rectangular Photomultiplier Tubes for Gamma-Ray Spectroscopy*. Kansas State University.

Capodaglio, A. (2017). Integrated, decentralized wastewater management for resource recovery in rural and Peri-urban areas. *Resources*, *6*(2), 22. https://doi.org/10.3390/resources6020022

Dada, M. A., Oliha, J. S., Majemite, M. T., Obaigbena, A., Sikhakhane Nwokediegwu, Z. Q., & Daraojimba, O. H. (2024). Review of nanotechnology in water treatment: Adoption in the USA and prospects for Africa. *World Journal of Advanced Research and Reviews*, *21*(1), 1412-1421. https://doi.org/10.30574/wjarr.2024.21.1.0170

Devarajan, Y. (2025). Nanomaterials-based wastewater treatment: Addressing challenges and advancing sustainable solutions. *BioNanoScience*, *15*(1). https://doi.org/10.1007/s12668-024-01780-8

Ejairu, U., Aderamo, A. T., Olisakwe, H. C., Esiri, A. E., Adanma, U. M., & Solomon, N. O. (2024). Eco-friendly wastewater treatment technologies (concept): Conceptualizing advanced, sustainable wastewater treatment designs for industrial and municipal applications. *Comprehensive Research and Reviews in Engineering and Technology*, *2*(1), 083-104. https://doi.org/10.57219/crret.2024.2.1.0063

Faheem, M., Azher Hassan, M., Du, J., & Wang, B. (2025). Harnessing potential of smart and conventional spent adsorbents: Global practices and sustainable approaches through regeneration and tailored recycling. *Separation and Purification Technology*, *354*, 128907. https://doi.org/10.1016/j.seppur.2024.128907

Feisal, N. A., Kamaludin, N. H., Ahmad, M. A., & Tengku Ibrahim, T. N. (2024). A comprehensive review of nanomaterials for efficient heavy metal ions removal in water treatment. *Journal of Water Process Engineering*, *64*, 105566. https://doi.org/10.1016/j.jwpe.2024.105566

Gleick, P. H. (2000). A look at twenty-first century water resources development. *Water International*, *25*(1), 127-138. https://doi.org/10.1080/02508060008686804

Isibor, P. O., Kayode-Edwards, I. I., & Taiwo, O. S. (2024). Emerging technology and future directions in environmental nanotoxicology. In *Environmental Nanotoxicology: Combatting the Minute Contaminants* (pp. 325-346). Cham: Springer Nature Switzerland.

Izatt, R. M., Izatt, S. R., Bruening, R. L., Izatt, N. E., & Moyer, B. A. (2014). Challenges to achievement of metal sustainability in our high-tech society. *Chem. Soc. Rev*, *43*(8), 2451-2475. https://doi.org/10.1039/c3cs60440c

Jan, I., Ahmad, T., Wani, M. S., Dar, S. A., Wani, N. A., Malik, N. A., & Tantary, Y. R. (2022). Threats and consequences of untreated wastewater on freshwater environments. In *Microbial consortium and biotransformation for pollution decontamination* (pp. 1-26). Elsevier.

Keshavan, S., Petri-Fink, A., & Rothen-Rutishauser, B. (2024). Understanding the benefits and risks of sustainable nanomaterials in a research environment. *CHIMIA*, *78*(6), 397-402. https://doi.org/10.2533/chimia.2024.397

Khan, M. N., & Mohammad, F. (2013). Eutrophication: Challenges and solutions. *Eutrophication: Causes, Consequences and Control*, 1-15. https://doi.org/10.1007/978-94-007-7814-6_1

Konstantopoulos, G., Koumoulos, E. P., & Charitidis, C. A. (2022). Digital innovation enabled Nanomaterial manufacturing; Machine learning strategies and green perspectives. *Nanomaterials*, *12*(15), 2646. https://doi.org/10.3390/nano12152646

Li, Q., Chen, Z., Wang, H., Yang, H., Wen, T., Wang, S., Hu, B., & Wang, X. (2021). Removal of organic compounds by nanoscale zero-valent iron and its composites. *Science of The Total Environment*, *792*, 148546. https://doi.org/10.1016/j.scitotenv.2021.148546

Liu, Y., He, X., Yuan, C., Cao, P., & Bai, X. (2024). Antifouling applications and fabrications of biomimetic micro-structured surfaces: A review. *Journal of Advanced Research*, *59*, 201-221. https://doi.org/10.1016/j.jare.2023.08.019

Mishra, B., Kumar, P., Saraswat, C., Chakraborty, S., & Gautam, A. (2021). Water security in a changing environment: Concept, challenges and solutions. *Water*, *13*(4), 490. https://doi.org/10.3390/w13040490

Nguyen, T. H., Nguyen, T. V., Vigneswaran, S., Ha, N. T., & Ratnaweera, H. (2023). A review of theoretical knowledge and practical applications of iron-based adsorbents for removing arsenic from water. *Minerals*, *13*(6), 741. https://doi.org/10.3390/min13060741

Nishu, & Kumar, S. (2023). Smart and innovative nanotechnology applications for water purification. *Hybrid Advances*, *3*, 100044. https://doi.org/10.1016/j.hybadv.2023.100044

Petala, E., Baikousi, M., Karakassides, M. A., Zoppellaro, G., Filip, J., Tuček, J., Vasilopoulos, K. C., Pechoušek, J., & Zbořil, R. (2016). Synthesis, physical properties and application of the zero-valent iron/titanium dioxide heterocomposite having high activity for the sustainable photocatalytic removal of hexavalent chromium in water. *Physical Chemistry Chemical Physics*, *18*(15), 10637-10646. https://doi.org/10.1039/c6cp01013j

Pham, H. D., Tekalgne, M. A., Do, H. H., Nguyen, V., Vo, D. N., Cheng, C. K., Shokouhimehr, M., Nguyen, C. C., Singh, P., Raizada, P., Kim, S. Y., & Le, Q. V. (2021). Emerging photocatalysts for air purification. *Materials Letters*, *288*, 129355. https://doi.org/10.1016/j.matlet.2021.129355

Prajapati, D., Jabborova, D., Saharan, B. S., Singh, N., Patani, A., Singh, S., & Joshi, C. (2024). Bionanotechnology: A paradigm for advancing environmental sustainability. *Indian Journal of Microbiology*. https://doi.org/10.1007/s12088-024-01389-1

Rahman, Z., & Singh, V. P. (2019). The relative impact of toxic heavy metals (THMs) (arsenic (As), cadmium (Cd), chromium (Cr)(VI), mercury (Hg), and lead (PB)) on the total environment: An overview. *Environmental Monitoring and Assessment*, *191*(7). https://doi.org/10.1007/s10661-019-7528-7

Sahoo, T., Sahu, J. R., Panda, J., Hembram, M., Sahoo, S. K., & Sahu, R. (2020). Nanotechnology: An efficient technique of contaminated water treatment. *Springer Transactions in Civil and Environmental Engineering*, 251-270. https://doi.org/10.1007/978-981-15-4599-3_11

Saleh, T. A. (2024). Materials, nanomaterials, nanocomposites, and methods used for the treatment and removal of hazardous pollutants from wastewater: Treatment technologies for water recycling and sustainability. *Nano-Structures & Nano-Objects*, *39*, 101231. https://doi.org/10.1016/j.nanoso.2024.101231

Samuel, M. S., Ravikumar, M., John J., A., Selvarajan, E., Patel, H., Chander, P. S., Soundarya, J., Vuppala, S., Balaji, R., & Chandrasekar, N. (2022). A review on green synthesis of nanoparticles and their diverse biomedical and environmental applications. *Catalysts*, *12*(5), 459. https://doi.org/10.3390/catal12050459

Saravanan, A., Deivayanai, V., Kumar, P. S., Rangasamy, G., Hemavathy, R., Harshana, T., Gayathri, N., & Alagumalai, K. (2022). A detailed review on advanced oxidation process in treatment of wastewater: Mechanism, challenges and future outlook. *Chemosphere*, *308*, 136524. https://doi.org/10.1016/j.chemosphere.2022.136524

Sharma, A., Goel, H., Sharma, S., Rathore, H. S., Jamir, I., Kumar, A., Thimmappa, S. C., Kesari, K. K., & Kashyap, B. K. (2024). Cutting edge technology for wastewater treatment using smart nanomaterials: Recent trends and futuristic advancements. *Environmental Science and Pollution Research*, *31*(48), 58263-58293. https://doi.org/10.1007/s11356-024-34977-1

Sun, Q., Zhang, X., Wang, Y., & Lu, A. (2015). Recent progress on core-shell nanocatalysts. *Chinese Journal of Catalysis*, *36*(5), 683-691. https://doi.org/10.1016/s1872-2067(14)60298-9

Tariq, A., & Mushtaq, A. (2023). Untreated wastewater reasons and causes: A review of most affected areas and cities. *Int. J. Chem. Biochem. Sci*, *23*(1), 121-143. https://www.iscientific.org/wpcontent/uploads/2023/05/15-IJCBS-23-23-22.pdf

Tawfik, W. (2024). A strategic review of the impact of modern technologies on scientific research: AI, lasers, and nanotechnology. *Journal of Laser Science and Applications*, *1*(2), 38-48. https://doi.org/10.21608/jlsa.2025.336891.1017

Verma, G., Mondal, K., Islam, M., & Gupta, A. (2024). Recent advances in advanced micro and Nanomanufacturing for wastewater purification. *ACS Applied Engineering Materials*, *2*(2), 262-285. https://doi.org/10.1021/acsaenm.3c00711

Vurro, M., Miguel-Rojas, C., & Pérez-de-Luque, A. (2019). Safe nanotechnologies for increasing the effectiveness of environmentally friendly natural agrochemicals. *Pest Management Science*, *75*(9), 2403-2412. https://doi.org/10.1002/ps.5348

Yan, Z., Ouyang, J., Wu, B., Liu, C., Wang, H., Wang, A., & Li, Z. (2024). Nonmetallic modified zero-valent iron for remediating halogenated organic compounds and heavy metals: A comprehensive review. *Environmental Science and Ecotechnology*, *21*, 100417. https://doi.org/10.1016/j.ese.2024.100417

Zaid, O., & El Ouni, M. H. (2024). Advancements in 3D printing of cementitious materials: A review of mineral additives, properties, and systematic developments. *Construction and Building Materials*, *427*, 136254. https://doi.org/10.1016/j.conbuildmat.2024.136254