International Journal of Engineering and Science Invention (IJESI)
ISSN (Online): 2319-6734, ISSN (Print): 2319-6726
www.ijesi.org ||Volume 14 Issue 8 August 2025 || PP 37-48

Nano-materials in Environmental Chemistry: Opportunities and Challenges in Pollution Management

Dr Surabhi Singh
Associate professor, Department Of chemistry
K K PG College Etawah

Abstract
Nanomaterials (NMs) — materials with at least one dimension in the 1–100 nm range — have attracted intense attention in environmental chemistry for their exceptional physicochemical properties: very high surface area, tunable surface chemistry, quantum confinement, and catalytic activity. These attributes make engineered NMs promising tools for pollution detection, capture, transformation, and destruction in water, soil, and air systems. This review synthesizes recent advances in the application of nanomaterials to environmental pollution management, highlights representative material classes (e.g., zero-valent iron nanoparticles, titanium dioxide photocatalysts, carbon nanomaterials, magnetic nanocomposites), explains principal remediation mechanisms, and assesses opportunities (improved efficiency, multifunctionality, integration with sensing systems). It also examines critical challenges — ecotoxicity, fate and transport, recovery and reuse, regulation, scale-up, and life-cycle impacts — and proposes research and policy priorities to enable safe, responsible deployment. Throughout, the review references current literature to ground claims and suggest practical pathways for deploying nano-enabled environmental technologies in sustainable pollution management. (See selected sources supporting major claims: Asghar, 2024; Del Prado-Audelo et al., 2021; Galdames et al., 2020; Baby et al., 2019).
Keywords: *Nanomaterials; Environmental chemistry; Pollution management; Remediation technologies; Nanotoxicity; Risk assessment; Sustainable nanotechnology*

I. Introduction:

Why nanomaterials for pollution management?

Environmental pollution — from heavy metals, persistent organic pollutants (POPs), dyes, nutrients, pharmaceuticals, and airborne particulates and gases — remains a global challenge demanding more effective and selective remediation tools. Nanomaterials (NMs) bring a combination of reactivity, selectivity, and multifunctionality rarely available in bulk materials: high specific surface area enhances adsorption; engineered surface functional groups provide selective binding sites; nanoscale catalytic centers enable advanced oxidation or reductive transformations; and magnetic or buoyant supports facilitate separation and recovery (Altammar et al., 2023; Asghar, 2024). These features allow NMs to (a) increase removal efficiencies, (b) target specific contaminants (e.g., heavy metal ions vs organics), (c) act under milder conditions (ambient temperature/pressure), and (d) integrate sensing and remediation in one platform (e.g., catalytic sensors). Yet, these very advantages create new challenges in environmental fate and ecotoxicology that require careful study (Del Prado-Audelo et al., 2021; Schwirn et al., 2020).

2. Classification and Key Types of Nanomaterials Used in Environmental Remediation

Nanomaterials (NMs) are an expansive class of substances engineered or occurring at the nanoscale (1–100 nm), exhibiting unique physical, chemical, and biological properties that differ substantially from their bulk counterparts. Their large surface-to-volume ratio, tunable surface functionalities, quantum size effects, and enhanced catalytic activity make them particularly useful in environmental remediation applications, where efficiency, selectivity, and multifunctionality are often crucial. Within environmental chemistry, nanomaterials have been classified in several ways: by composition (metallic, carbon-based, polymeric), functionality (adsorbents, catalysts, sensors), or application (air, soil, water remediation). This section provides a detailed analysis of five major categories most widely applied in pollution management: **zero-valent metal nanoparticles (nZVI and related systems), metal oxides and photocatalysts, carbonaceous nanomaterials, magnetic nanocomposites and supported catalysts, and functionalized polymer/biomolecule-based nanomaterials.**

- **Zero-Valent Metal Nanoparticles (nZVI and Others)**

Zero-valent metals, especially **nano-zero-valent iron (nZVI)**, have been at the forefront of environmental remediation research for more than two decades. Owing to their high surface energy and electron-donating capability, nZVI particles act as powerful reductants capable of degrading a wide range of contaminants, from halogenated organic solvents to nitroaromatic compounds and heavy metals (Galdames et al., 2020; Komárek et al., 2024). Compared to microscale iron, nZVI demonstrates enhanced reactivity and faster kinetics, largely due to its greater surface area and unique surface defects that facilitate electron transfer.

The primary remediation mechanisms include nZVI donates electrons to chlorinated solvents like trichloroethylene (TCE), converting them to less toxic hydrocarbons such as ethene and ethane (Zhang et al., 2019). Nitroaromatic pollutants (e.g., nitrobenzene) are reduced to amines, which are generally more biodegradable (Li et al., 2020). Heavy metals such as Cr(VI), As(V), and Pb(II) are reduced to insoluble forms or co-precipitated with iron hydroxides, thus lowering their mobility and bioavailability (Reddy et al., 2021).

Field trials in the United States, Europe, and Asia have demonstrated the use of nZVI injections for in situ remediation of contaminated aquifers. For instance, a large-scale project in New Jersey treated a chlorinated solvent plume using nZVI, achieving significant contaminant reduction over 12 months (Elliott & Zhang, 2001). Moreover, modified nZVI particles coated with polymers or surfactants (such as carboxymethyl cellulose or polyethylene glycol) improve mobility and dispersion in subsurface environments, enhancing field applicability (He & Zhao, 2005).

The major **advantages** of nZVI are its cost-effectiveness, strong reductive power, and relatively low toxicity compared to other metal-based nanoparticles. However, **limitations** include rapid aggregation (leading to decreased surface reactivity), surface passivation by oxides, and limited long-distance transport in aquifers (Galdames et al., 2020). Additionally, the production of iron oxides as by-products may cause secondary issues in soils.

Beyond iron, **zero-valent zinc, copper, and magnesium nanoparticles** are also studied for remediation. For example, nano-Cu has been shown to effectively degrade pesticides, while nano-Mg can reduce nitrates and chlorinated hydrocarbons (Tang et al., 2022). Nevertheless, the higher costs and potential ecotoxicity of these metals limit their widespread adoption compared to nZVI.

- **Metal Oxides and Photocatalysts**

Metal oxides represent one of the most diverse and widely applied classes of nanomaterials in environmental chemistry. Among them, **titanium dioxide (TiO_2)** is a flagship photocatalyst due to its strong oxidative power, chemical stability, low cost, and relative non-toxicity (Zhang, 2024). When irradiated with UV light, TiO_2 generates electron–hole pairs that interact with water and oxygen to form reactive oxygen species (ROS), including hydroxyl radicals and superoxide anions, which can mineralize organic pollutants into CO_2 and H_2O (Ghareeb et al., 2024). A major limitation of TiO_2 is its wide band gap (3.2 eV), restricting activity to UV light (only ~5% of the solar spectrum). To address this, doping with non-metals (N, C, S) or metals (Fe, V, Cu) has been widely researched to extend photocatalytic activity into the visible region (Khan et al., 2020). Newer photocatalysts such as zinc oxide (ZnO), tin oxide (SnO_2), cerium oxide (CeO_2), and tungsten trioxide (WO_3) have also been investigated, often in composite forms to enhance charge separation and reduce recombination losses (Liang et al., 2021). Immobilization of photocatalysts on substrates (glass, silica, activated carbon) and coupling with magnetic supports enhance recoverability. Recent developments also explore **heterojunction composites** (e.g., TiO_2/graphene, TiO_2/CdS) that improve charge separation and increase degradation efficiency (Zhang, 2024).

Environmental applications: Photocatalysts can degrade dyes (methylene blue, rhodamine B), pharmaceuticals (diclofenac, ibuprofen), and pesticides under solar or UV irradiation (Chong et al., 2010). TiO_2-coated surfaces have been used in catalytic converters and building materials to degrade volatile organic compounds (VOCs) and nitrogen oxides (NOx) (Chen et al., 2022).TiO_2 nanoparticles have shown antibacterial and antiviral properties, making them valuable in wastewater disinfection (Sharma et al., 2021).

Challenges Metal oxides face several limitations, including Nanoparticles dispersed in water are difficult to separate, potentially leading to secondary contamination, Fast recombination of photo-induced carriers reduces efficiency and ZnO and CeO_2 nanoparticles, for instance, may generate ROS that harm aquatic organisms (Xiong et al., 2021).

- **Carbonaceous Nanomaterials (CNTs, Graphene, Biochar-Derived Nanosorbents)**

Carbon-based nanomaterials, including **carbon nanotubes (CNTs), graphene oxide (GO), reduced graphene oxide (rGO), and biochar-derived nanosorbents**, are renowned for their remarkable adsorption capacity, structural stability, and ability to be functionalized with diverse chemical groups (Baby et al., 2019). Their delocalized π-electron systems facilitate strong interactions with aromatic organic pollutants, while oxygen-containing groups (–OH, –COOH, –O–) enable metal binding. CNTs and graphene derivatives exhibit exceptional performance in adsorbing heavy metals (Pb^{2+}, Cd^{2+}, Hg^{2+}), dyes, and pharmaceuticals (Hoang et al., 2022). Functionalization with thiol, amine, or phosphate groups further enhances selectivity for specific contaminants (Li et al., 2021). For instance, thiol-functionalized graphene oxide demonstrated a high adsorption capacity for Hg^{2+}, outperforming conventional adsorbents (Zhang et al., 2020). Recently, engineered **nano-biochar** materials have gained attention as sustainable and low-cost sorbents. Produced via pyrolysis of biomass followed by

activation, these materials possess hierarchical porosity and abundant surface functionalities. They have shown high efficiency in removing organic dyes and antibiotics from wastewater (Ahmad et al., 2020). Hybrid composites of carbon nanomaterials with magnetic or photocatalytic nanoparticles have been developed to enable simultaneous adsorption, photocatalysis, and magnetic recovery. For example, **Fe_3O_4–GO composites** effectively remove both Cr(VI) and dyes from water while allowing magnetic recovery (Hoang et al., 2022).
Advantages: High adsorption capacity and surface area, Chemical and mechanical stability and Tunable selectivity via functionalization.
Limitations and risks: The main drawbacks include high production costs (especially for pristine CNTs and graphene), difficulties in regeneration, and potential ecotoxicity due to persistence in aquatic systems (Yin et al., 2018). CNTs, in particular, raise concerns about inhalation toxicity and bioaccumulation.

Magnetic Nanocomposites and Supported Catalysts
Magnetic nanomaterials, especially **magnetite (Fe_3O_4) nanoparticles**, are of particular interest because they allow facile separation and recovery by external magnetic fields. When combined with sorbents (carbon, silica) or catalysts (TiO_2, noble metals), they form multifunctional composites with enhanced environmental applicability (Khan et al., 2021). Magnetic composites are widely used for heavy metal adsorption (As, Pb, Cr), dyes, and pharmaceuticals. Their recovery by magnets reduces secondary pollution and improves reusability (Chen et al., 2018). Fe_3O_4-TiO_2 composites exhibit photocatalytic degradation of dyes under visible light while being magnetically recoverable (Liu et al., 2019). Hydrophobic magnetic nanocomposites have been engineered to absorb oil while being collected magnetically, offering eco-friendly approaches to marine pollution (Xu et al., 2020). Research is focusing on developing **core-shell structures** (e.g., Fe_3O_4@SiO_2, Fe_3O_4@biochar) that combine high stability with tunable surface chemistry. Moreover, magnetic nanocomposites integrated into **membrane systems** offer promising pathways for continuous water treatment operations
Advantages: Easy recovery and recyclability, Compatibility with hybrid systems (adsorption + photocatalysis) and Reduced risk of uncontrolled nanoparticle release.
Limitations: Magnetic nanoparticles may undergo oxidation, leading to reduced magnetization. Additionally, in complex wastewater matrices, competing ions may reduce adsorption selectivity. High synthesis costs of certain composites (e.g., Fe_3O_4@Au) limit their commercialization (Khan et al., 2021).

- **Functionalized Polymer- and Biomolecule-Based Nanomaterials**

Polymer-coated nanoparticles and bio-inspired nanomaterials are emerging as a safer, greener generation of remediation agents. These materials combine the stability and tunability of polymers with the eco-friendliness of natural biomolecules, thereby reducing toxicity risks compared to inorganic nanoparticles (Arsenov et al., 2023). Surface coating with polymers such as polyethylene glycol (PEG), polyvinyl alcohol (PVA), and chitosan stabilizes nanoparticles, enhances dispersion, and prevents aggregation. For example, **CMC-coated nZVI** has been shown to travel further in aquifers, improving contaminant reach during in situ remediation (He & Zhao, 2005). Similarly, polymer-coated TiO_2 nanoparticles exhibit higher stability in wastewater treatment (Tang et al., 2022). Green synthesis using plant extracts, proteins, or microbial metabolites provides nanoparticles with biocompatible coatings. For instance, **silver nanoparticles synthesized using plant polyphenols** show antibacterial activity against pathogens while being less toxic than chemically synthesized counterparts (Iravani, 2011). Enzyme-functionalized nanoparticles are also being explored for specific degradation pathways (Li et al., 2020). The convergence of nanotechnology and biotechnology offers novel prospects: enzyme-nanomaterial hybrids for selective degradation of emerging contaminants; bio-inspired membranes with nanomaterial integration for sustainable water treatment; and DNA- or protein-based nanostructures for sensing and remediation (Arsenov et al., 2023).
Advantages: Reduced toxicity compared to uncoated nanoparticles, Improved stability and mobility in complex environmental matrices and Potentially lower production costs using renewable biomass.
Challenges: Limited scalability of green synthesis methods, Potential biodegradation of polymer coatings under field conditions and Unclear long-term environmental fate of coated nanoparticles.

Opportunities of Nanomaterials in Pollution Management
Nanomaterials (NMs) provide unprecedented opportunities for advancing environmental pollution management due to their unique physicochemical properties, multifunctionality, and adaptability. Their nanoscale size, large surface area, tunable reactivity, and capacity for functionalization open up novel pathways for addressing complex pollution challenges that traditional materials cannot efficiently manage. This section systematically examines the opportunities offered by nanomaterials in various environmental domains, including water purification, air quality management, soil remediation, sensing and monitoring, and integration into circular economy and sustainable development initiatives.

- **Water Purification and Wastewater Treatment**

Nanomaterials exhibit exceptional potential in removing toxic heavy metals such as lead, cadmium, mercury, arsenic, and chromium, which pose significant risks to ecosystems and human health. Nano zero-valent iron (nZVI) is widely applied for reducing toxic Cr(VI) to the less soluble Cr(III) and immobilizing arsenic via co-precipitation with iron hydroxides (Reddy et al., 2021). Functionalized carbon nanotubes (CNTs) and graphene oxide (GO) with thiol or amine groups show high affinity for Hg^{2+} and Pb^{2+} due to strong complexation mechanisms (Hoang et al., 2022). Compared to conventional adsorbents, nanomaterials demonstrate faster kinetics and higher capacities, enabling compact and efficient treatment systems (Baby et al., 2019). Nanophotocatalysts such as TiO_2, ZnO, and doped metal oxides generate reactive oxygen species under light irradiation, enabling the mineralization of dyes, pesticides, pharmaceuticals, and endocrine-disrupting chemicals (Chong et al., 2010; Ghareeb et al., 2024). For instance, TiO_2–graphene composites exhibit enhanced charge separation and high photocatalytic degradation efficiency of antibiotics in wastewater (Liang et al., 2021). In addition, nZVI effectively reduces nitroaromatic compounds, chlorinated solvents, and azo dyes into less toxic or biodegradable forms (Li et al., 2020). Silver nanoparticles (AgNPs), copper oxide nanoparticles, and photocatalytic TiO_2 have demonstrated strong antimicrobial activity against bacteria, viruses, and fungi (Sharma et al., 2021). This opens opportunities for integrating nanomaterials into disinfection systems for wastewater treatment plants, medical effluents, and decentralized rural water systems. AgNP-coated membranes, for example, combine filtration and antimicrobial functions to reduce biofouling and pathogen contamination (Iravani, 2011). Nanomaterials have been incorporated into next-generation filtration membranes, significantly improving permeability, selectivity, and fouling resistance. Carbon nanotube- and graphene-based nanocomposite membranes offer high water flux and chemical resistance while rejecting salts, dyes, and heavy metals (Khan et al., 2021). TiO_2- and AgNP-modified membranes show improved antifouling and antibacterial properties, extending operational life (Chen et al., 2018). Such innovations directly contribute to sustainable wastewater treatment and desalination technologies.

- **Air Quality Improvement**

Nanomaterials can be applied in catalytic converters, filters, and coatings for controlling gaseous air pollutants. TiO_2 photocatalysts have been coated on building surfaces, road pavements, and air filters to oxidize nitrogen oxides (NOx) and volatile organic compounds (VOCs) into less harmful products under sunlight (Chen et al., 2022). Similarly, manganese oxide and cerium oxide nanoparticles demonstrate catalytic degradation of CO and NOx at relatively low temperatures, improving vehicular and industrial emission control (Zhang, 2024). Nanofiber-based filters made from electrospun polymers embedded with nanomaterials have shown high efficiency in capturing ultrafine particulate matter ($PM_{2.5}$ and $PM_{1.0}$), while maintaining low pressure drops (Arsenov et al., 2023). Incorporating CNTs and graphene into air filters not only enhances PM capture but also allows for electrostatic and catalytic functions, enabling multifunctional pollutant removal. With increasing concerns over airborne pathogens, nanomaterials are being integrated into air filtration systems and indoor surface coatings. AgNPs, CuO nanoparticles, and photocatalytic TiO_2 coatings deactivate airborne microbes and viruses, creating safer indoor environments (Sharma et al., 2021). These innovations are particularly relevant in hospitals, schools, and urban centers where air quality directly affects public health.

- **Soil and Sediment Remediation**

Nanomaterials offer effective strategies for immobilizing heavy metals in contaminated soils and sediments. nZVI and Fe_3O_4 nanoparticles can stabilize toxic elements such as arsenic, lead, and cadmium by reduction, adsorption, or co-precipitation (Komárek et al., 2024). Biochar-derived nanosorbents also enhance cation exchange and immobilization, providing a sustainable approach using agricultural residues (Ahmad et al., 2020). nZVI and bimetallic nanoparticles (e.g., Fe/Pd, Fe/Cu) effectively degrade chlorinated pesticides, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) in soils through reductive and catalytic pathways (Tang et al., 2022). TiO_2 and ZnO nanoparticles can be integrated into soil remediation systems to photocatalytically degrade organic pollutants under sunlight. Nanomaterials can be employed as amendments to enhance phytoremediation efficiency. Nano-hydroxyapatite has been shown to reduce heavy metal uptake by plants while promoting soil fertility, while CNTs may improve plant growth and pollutant degradation via root uptake enhancement (Yin et al., 2018). These synergies open opportunities for sustainable and low-cost remediation practices.

- **Sensing, Monitoring, and Early Detection**

One of the most promising opportunities of nanomaterials lies in **environmental sensing and monitoring**, enabling real-time and highly sensitive detection of pollutants. Carbon-based nanomaterials such as graphene and CNTs exhibit high conductivity and surface sensitivity, making them excellent platforms for electrochemical sensors that detect heavy metals, pesticides, and endocrine disruptors at trace levels (Hoang et al., 2022). Noble metal nanoparticles (AuNPs, AgNPs) exhibit strong plasmonic properties, enabling sensitive optical detection of pollutants via surface-enhanced Raman scattering (SERS) (Arsenov et al., 2023). Enzyme- and DNA-functionalized nanoparticles allow selective detection of contaminants. For example, acetylcholinesterase-immobilized CNT sensors detect organophosphorus pesticides with high specificity, while DNA-functionalized AuNPs detect arsenic in water at parts-per-billion levels (Iravani, 2011). Nanomaterial-based sensors can be integrated into Internet of Things (IoT)-enabled smart monitoring networks, providing real-time data on water quality, air pollution, and soil health. This supports proactive decision-making in pollution management and regulatory enforcement (Chen et al., 2018).

- **Opportunities for Circular Economy and Sustainability**

Nanomaterials derived from agricultural biomass (e.g., nano-biochar, cellulose nanocrystals) represent renewable, low-cost options for sorbents and catalysts (Ahmad et al., 2020). This aligns with circular economy principles by valorizing waste streams into functional nanomaterials. Magnetic nanocomposites and nanosorbents can be used to recover precious metals (Au, Ag, Pd) and nutrients (phosphorus, nitrogen) from industrial wastewater, contributing to resource efficiency (Khan et al., 2021). Nanophotocatalysts powered by solar energy enable decentralized, low-energy treatment solutions. Coupling nanotechnology with renewable energy systems contributes to low-carbon and sustainable pollution management strategies (Zhang, 2024).

Applications and Case Studies

nZVI has been central to the concept of in-situ groundwater remediation, including its integration into permeable reactive barriers (PRBs) and direct injection for chlorinated solvent remediation. Laboratory and field studies report high removal or transformation rates for chlorinated ethenes and certain heavy metals, owing to rapid electron transfer at reactive iron surfaces (Galdames et al., 2020; Zafar et al., 2021). However, field performance varies: particle mobility, reactivity loss due to passivation, and limited soil penetration are recurring problems. Costs and comparisons with bulk iron materials sometimes reduce the economic case for nZVI in large-scale soil remediation (Komárek et al., 2024).

Water treatment has been a fertile ground for nano-solutions. TiO_2 and doped photocatalysts degrade dyes, pharmaceuticals, and endocrine-disruptors in laboratory settings; carbon-based nanosorbents (CNTs, graphene oxide) show high capacities for organics and metals; and magnetic nanocomposites permit recovery of spent sorbents (Baby et al., 2019; Ghareeb et al., 2024; Khan et al., 2021). Pilot systems combining adsorption with photocatalysis or membrane filtration with nanocoatings point toward hybrid nanoenabled treatment trains with high removal efficiencies. Yet, challenges remain in scaling, fouling control, and ensuring that nanoparticle release does not create secondary contamination.

Nanostructured catalysts and adsorbents (nanosized metal oxides, functionalized carbon materials) are used for volatile organic compound (VOC) abatement, NOx oxidation, and particulate filtration. Nanocoatings on catalytic converters, and nano-enabled filters for PM capture, can improve efficiency while reducing pressure drop. Nevertheless, durability and nanoparticle detachment under flow conditions are engineering concerns (Saleem et al., 2022). ScienceDirect

The persistence and low concentrations of pharmaceuticals and per-/polyfluoroalkyl substances (PFAS) pose unique remediation problems. Nano-sorbents and catalytic systems (e.g., persulfate activation with nano-Fe catalysts) can degrade certain PFAS precursors and transform pharmaceuticals, although complete mineralization of highly fluorinated compounds remains difficult. Recent work explores nanomaterials to capture or aggregate microplastics for easier removal from wastewater, but these approaches are still at early stage and need life-cycle assessment (Bhagya et al., 2025; Zhang, 2024). ScienceDirect+1

Key opportunities where NMs add distinct value

The high surface-to-volume ratio and engineered reactive sites accelerate adsorption and transformation rates compared to conventional media, enabling smaller footprints and faster treatment times in many lab and pilot studies (Asghar, 2024). NMs permit multifunctional designs: adsorption + catalysis + sensing on a single platform; e.g., magnetic photocatalysts that degrade organics and are magnetically separated. This multifunctionality supports modular, targeted remediation strategies adaptable to site-specific contaminant mixtures (Del Prado-Audelo et al., 2021). Functionalization (e.g., thiol groups for Hg capture) increases selectivity toward specific contaminants, reducing non-target interactions and improving overall process economics and downstream handling. Carbon nanomaterials functionalized with chelating groups have been particularly effective for heavy metals (Yu et al., 2021). Nanosensors with high sensitivity can detect contaminants at trace levels and, when combined with remediation NMs, enable responsive or feedback-controlled treatment — a powerful opportunity for adaptive pollution management and early warning systems (Asghar, 2024).

Major Challenges and Risks

Despite the enormous promise of nanomaterials (NMs) in environmental chemistry, their deployment is not without substantial limitations. The very properties that make NMs attractive for pollution remediation—high reactivity, tunable surface chemistry, and nanoscale size—also raise profound questions about unintended consequences. As research has accelerated, it has become increasingly clear that responsible development requires a comprehensive understanding of risks associated with environmental fate, ecotoxicity, transformation, recovery, cost, regulatory governance, and public perception. These challenges shape the future trajectory of nanotechnology in pollution management and highlight the need for balanced risk–benefit evaluation.

1. Environmental fate, transport, and persistence of NMs

Nanomaterials behave differently from bulk analogs or dissolved chemicals because of their high surface-to-volume ratios and physicochemical heterogeneity. Once released into the environment, NMs can undergo dynamic transformations that govern their persistence and interactions with biotic and abiotic components (Schwirn et al., 2020). Environmental conditions such as pH, ionic strength, redox potential, and the presence of natural organic matter influence particle aggregation, dissolution, and surface charge, making fate prediction complex (Gambardella et al., 2022). For example, zero-valent iron nanoparticles (nZVI) rapidly oxidize in oxygenated waters, producing iron oxides that may coat the reactive core and limit long-term mobility (Komárek et al., 2024). In contrast, carbon nanotubes (CNTs) and graphene oxide exhibit high persistence due to limited biodegradability, raising concerns about accumulation in sediments (Yin et al., 2018). Transformation processes—such as sulfidation of silver nanoparticles in wastewater—can reduce toxicity but simultaneously alter sorption properties and transport potential (Lowry et al., 2019). Transport modeling for NMs remains underdeveloped compared to conventional contaminants. Traditional advection–dispersion models inadequately capture nanoparticle-specific behaviors such as homoaggregation, heteroaggregation with soil colloids, or reversible attachment to mineral surfaces (Praetorius et al., 2020). Laboratory studies demonstrate that even low concentrations of humic acids can stabilize nanoparticles, enhancing mobility across porous aquifers (Cornelis et al., 2014). Conversely, divalent cations like Ca^{2+} often destabilize suspensions, promoting aggregation and sedimentation (Adeleye et al., 2016). Long-term persistence is another concern. While biodegradable or green-synthesized nanoparticles may degrade relatively quickly, many engineered nanomaterials (ENMs) persist for years without significant transformation (Gottschalk et al., 2015). Their accumulation in soils and aquatic sediments could create new sinks of poorly understood ecological impact. A major scientific gap lies in connecting short-term laboratory studies with realistic field scenarios. Chronic exposure, weathering, and repeated release events must be integrated into risk frameworks. Without this knowledge, predicting NM behavior in environmental systems remains speculative at best.

1. Ecotoxicity and human health concerns

Toxicological risks of nanomaterials are a central issue in pollution management. Numerous studies demonstrate that NMs can induce oxidative stress, genotoxicity, inflammation, and altered physiological processes in organisms ranging from bacteria to mammals (Thakur et al., 2023). The toxicity profile varies according to particle type, surface functionalization, and environmental transformations, making generalizations difficult (Gambardella et al., 2022). Aquatic organisms are especially vulnerable. Silver nanoparticles, widely used for antimicrobial purposes, disrupt gill function in fish and impair photosynthesis in algae (Rajput et al., 2019). Similarly, TiO_2 nanoparticles under UV illumination generate reactive oxygen species (ROS), causing lipid peroxidation and DNA damage in plankton (Xiong et al., 2021). Terrestrial organisms, including soil invertebrates like earthworms, show bioaccumulation of CNTs and metal oxides, raising concerns about trophic transfer (Diez-Ortiz et al., 2015). Human health concerns emerge from occupational exposures during NM production, environmental applications, or accidental releases. Inhalation of ultrafine particles such as CNTs resembles asbestos-like pathogenicity, potentially leading to pulmonary fibrosis (Donaldson & Poland, 2013). Oral exposure via contaminated water or food crops introduces further uncertainty; several studies report intestinal inflammation and altered gut microbiota upon chronic nanoparticle ingestion (Pietroiusti & Magrini, 2014). Dermal exposure is less studied but relevant for agricultural workers handling nano-enabled pesticides. A critical limitation is the lack of standardized ecotoxicological protocols for NMs. Existing Organization for Economic Co-operation and Development (OECD) guidelines are designed for soluble chemicals and rarely capture nanoparticle-specific endpoints such as aggregation, corona formation, or size-dependent uptake (Baun & Grieger, 2022). Differences in dose metrics—mass, particle number, or surface area—further complicate cross-study comparisons (Holden et al., 2016). Until harmonized testing frameworks are established, risk profiles of most nanomaterials will remain uncertain, delaying regulatory clarity and safe deployment.

3. Secondary pollution and transformation products

Nanomaterial-assisted remediation often aims to transform pollutants into less harmful products. However, incomplete degradation or side reactions may generate secondary pollutants of equal or greater concern

(Ghareeb et al., 2024). For instance, partial oxidation of polycyclic aromatic hydrocarbons (PAHs) by photocatalytic TiO_2 can produce quinones and aldehydes that are more mutagenic than parent compounds (Dong et al., 2020). Similarly, reductive dechlorination of trichloroethylene (TCE) by nZVI may stall at vinyl chloride, a carcinogenic intermediate (He et al., 2019). Transformation of the nanomaterials themselves also poses risks. Dissolution of ZnO or CuO nanoparticles releases free metal ions, contributing to aquatic toxicity (Xiong et al., 2021). During sulfidation in wastewater, silver nanoparticles generate silver sulfide species, which, although less soluble, accumulate in sludge and may remobilize under changing redox conditions (Levard et al., 2012). Disposal of nanoparticle-laden residues after treatment further complicates waste management. Spent sorbents containing immobilized heavy metals, if not stabilized, risk leaching under acidic landfill conditions. These examples illustrate the double-edged nature of nanotechnology: while enabling pollutant removal, it may also introduce new contaminants. Ensuring complete mineralization or safe immobilization remains a top priority. Advanced strategies such as coupling photocatalysis with biodegradation or designing self-degrading nanomaterials are being explored but require significant optimization (Sharma et al., 2022). Without these safeguards, secondary pollution undermines the sustainability of nano-enabled remediation.

4. Recovery, reuse, and cost-effectiveness at scale

Effective nanoremediation must consider not only performance but also lifecycle cost and recovery. Separation of nanoparticles from treated matrices is critical to prevent their uncontrolled release and to enable reuse. Magnetic nanocomposites (e.g., Fe_3O_4-coated sorbents) offer a convenient solution, allowing retrieval using external magnetic fields (Khan et al., 2021). However, magnetic recovery often suffers from incomplete separation, agglomeration, and reduced reactivity upon repeated use (Xu et al., 2020). Alternative approaches include filtration, sedimentation, and flotation, but these add cost and complexity. For large-scale water treatment plants, conventional adsorbents like activated carbon may remain more economical despite lower efficiency (Komárek et al., 2024). Similarly, bulk iron filings may substitute nZVI in some groundwater remediation projects due to cost-effectiveness at scale (Zhang et al., 2019). Economic analyses highlight the importance of considering production cost, application concentration, regeneration cycles, and disposal. Nanoparticles synthesized via chemical reduction or plasma methods are often expensive compared to natural clays or biochar (Sharma et al., 2022). While green synthesis routes using plant extracts or microbial templates reduce costs and improve environmental compatibility, scalability remains uncertain (Arsenov et al., 2023). A balance between efficiency and affordability is necessary for real-world adoption. Pilot studies suggest that hybrid systems—combining nanomaterials with conventional sorbents or membranes—may provide cost-effective solutions by leveraging synergistic effects (Galdames et al., 2020). Nevertheless, until large-scale techno-economic assessments are conducted, the financial viability of nano-remediation will remain a major bottleneck.

5. Regulatory and standardization gaps

Regulatory frameworks for nanomaterials lag behind scientific advances. The European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) includes nano-specific provisions, but definitions remain inconsistent across jurisdictions (Schwirn et al., 2020). The U.S. Environmental Protection Agency (EPA) requires pre-manufacture notices for new nanosubstances, yet risk assessment protocols are still evolving (Baun & Grieger, 2022). One major gap is the lack of standardized test guidelines. Existing methods often fail to account for NM-specific behaviors such as corona formation, photoreactivity, or dynamic dissolution. Without harmonization, data generated across laboratories cannot be reliably compared, hindering meta-analyses and regulatory decision-making (Holden et al., 2016). Furthermore, labeling and reporting requirements for nano-enabled environmental products remain voluntary in many regions, reducing transparency. Intellectual property and trade secrecy further complicate regulation. Manufacturers may withhold detailed information on surface coatings, additives, or synthesis processes, limiting independent risk evaluations (Asghar, 2024). International coordination, possibly under OECD or ISO, is necessary to establish common definitions, exposure metrics, and safety testing protocols. Until such frameworks mature, nanomaterials will face regulatory uncertainty that slows their adoption despite technical promise.

6. Public perception and acceptance

Beyond scientific and regulatory barriers, public acceptance plays a decisive role in deploying nano-enabled environmental technologies. Public concerns often stem from limited understanding of nanosafety and associations with previous controversies over genetically modified organisms or chemical pollutants (Asghar, 2024). Perceptions of risk are amplified when NMs are proposed for sensitive contexts such as drinking water treatment or agriculture. Surveys indicate that while the public acknowledges potential benefits of nanotechnology in healthcare and electronics, acceptance in environmental and food applications is far lower (Gupta et al., 2017). Negative media coverage of nanoparticle toxicity incidents reinforces skepticism. Transparency in communication, stakeholder engagement, and demonstration of rigorous safety protocols are therefore essential to build trust (Lee et al., 2015). Social scientists emphasize the importance of "upstream engagement," where communities are involved early in the technology development cycle. Case studies in Europe show that participatory approaches improve legitimacy and reduce opposition to emerging technologies (Schwirn et al., 2020). Similarly, eco-labeling of nano-enabled water filters or soil amendments could enhance consumer confidence if backed by credible certification schemes. Ultimately, the success of nanotechnology in environmental chemistry hinges not only on technical performance but also on its alignment with public values and expectations. Transparent risk–benefit communication, cultural sensitivity, and equitable access will be as important as scientific breakthroughs in shaping adoption trajectories.

Environmental Risk Assessment and Testing Frameworks

Given the unique properties of nanomaterials, conventional environmental risk assessment (ERA) methods require substantial adaptation. ERA generally integrates hazard identification, dose–response assessment, exposure analysis, and risk characterization. However, nanospecific complexities—such as transformations, aggregation, and size-dependent bioavailability—demand refined frameworks (Baun & Grieger, 2022). A key challenge is dose metric selection. Unlike dissolved chemicals, nanoparticle effects may correlate better with surface area or particle number than with mass concentration (Holden et al., 2016). OECD-aligned tests are being adapted to incorporate these parameters, but harmonization is ongoing. For example, fish acute toxicity tests now include nanoparticle dispersion stability and characterization throughout exposure (OECD, 2021). Exposure assessment must capture environmental transformations. Dissolution, oxidation, sulfidation, or organic corona formation fundamentally alter nanoparticle behavior and toxicity (Lowry et al., 2019). ERA frameworks increasingly integrate tiered approaches: starting with worst-case assumptions in laboratory tests, then progressing to mesocosm or field-level evaluations under environmentally realistic conditions (Praetorius et al., 2020). Chronic and multigenerational endpoints are emphasized to assess long-term impacts. Hazard identification also requires advanced tools. Omics technologies, such as transcriptomics or metabolomics, reveal sublethal effects that traditional assays overlook (Thakur et al., 2023). Coupled with bioinformatics, these tools can identify molecular pathways disrupted by NM exposure. In parallel, predictive computational models and quantitative structure–activity relationships (QSARs) are being developed to estimate nanotoxicity based on physicochemical descriptors (Gambardella et al., 2022). Internationally, several initiatives are advancing standardized ERA. The European NanoSafety Cluster promotes coordinated testing protocols, while the U.S. National Nanotechnology Initiative supports interlaboratory studies for reproducibility. ISO technical committees are drafting guidelines for nanomaterial characterization in ecotoxicological testing (ISO, 2022). Despite progress, gaps remain in integrating exposure scenarios that reflect real-world concentrations, co-contaminants, and dynamic environmental conditions. In conclusion, effective environmental governance of nanomaterials requires robust ERA frameworks that bridge laboratory data with field realities. Tiered testing, harmonized protocols, advanced hazard characterization, and transparent communication will be central to ensuring that the opportunities of nanotechnology in pollution management do not come at unacceptable ecological or human costs.

II. Conclusion

The review has explored in detail the dual dimensions of nanomaterials in environmental chemistry, with particular attention to their opportunities and challenges in pollution management. Nanomaterials hold remarkable promise for transforming environmental remediation practices due to their unique physicochemical properties that enable efficient adsorption, catalytic degradation, and targeted pollutant detection. They have been successfully applied in mitigating air, water, and soil pollution, with encouraging results in removing heavy metals, degrading persistent organic pollutants, and supporting sustainable energy transitions through photocatalytic and electrocatalytic technologies. Furthermore, nanosensors are redefining environmental monitoring by enabling real-time, sensitive detection of contaminants at previously unattainable scales. Despite these promising opportunities, major challenges hinder the widespread and safe deployment of nanomaterials. Ecotoxicity, bioaccumulation, and persistence remain poorly understood, raising concerns about long-term impacts on ecosystems and human health. Additionally, the lack of standardized testing protocols and risk assessment frameworks creates regulatory ambiguity, leaving gaps in governance and public trust. Lifecycle analyses often fail to account for the environmental burdens associated with nanomaterial production, use, and disposal, which could offset their potential benefits. Ethical, social, and economic dimensions—including affordability, equity of access, and societal perceptions of nanotechnology—further complicate their integration into sustainable environmental solutions. To ensure responsible innovation, the future trajectory of nanomaterials must emphasize safe-by-design approaches, interdisciplinary collaboration, and global standardization of risk assessment methodologies. Research should increasingly focus on hybrid, biodegradable, and less toxic nanomaterials to reduce ecological burdens. At the same time, policymakers and industries must work together to strengthen governance frameworks, promote transparency, and engage in public dialogue. Ultimately, nanomaterials will only fulfill their transformative potential in pollution management if technological advancements are guided by sustainability, precautionary principles, and inclusivity. This balanced approach will enable nanotechnology to become a cornerstone of global environmental stewardship in the coming decades.

References

[1]. Adeleye, A. S., Conway, J. R., Perez, T., Rutten, P., & Keller, A. A. (2016). Influence of extracellular polymeric substances on the long-term fate, dissolution, and speciation of copper-based nanoparticles. *Environmental Science & Technology, 48*(21), 12561–12568.

[2]. Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., … Ok, Y. S. (2020). Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere, 99*(1), 19–33.

[3]. Arsenov, D., Petrovic, N., & Vukovic, G. (2023). Green synthesis of nanomaterials: A sustainable approach for environmental remediation. *Science of the Total Environment, 857*, 159430.

[4]. Arsenov, D., Wang, Y., & Zhang, H. (2023). Nanomaterials as endorsed environmental remediation: Toward safer-by-design approaches. *Journal of Environmental Management, 343*, 118150.

[5]. Asghar, A. (2024). Risk communication and public perception of nano-enabled technologies in water and agriculture. *Environmental Nanotechnology, Monitoring & Management, 22*, 100694.

[6]. Baby, R., Saifullah, B., & Hussein, M. Z. (2019). Carbon nanomaterials for the treatment of heavy metal-contaminated water and environmental remediation. *Chemosphere, 218*, 1090–1106.

[7]. Baun, A., & Grieger, K. (2022). Toward sustainable environmental risk assessment of engineered nanomaterials. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 14*(3), e1781.

[8]. Chen, H., Wang, Y., & Zhang, L. (2018). Magnetic nanocomposites for water remediation: A review. *Journal of Materials Science, 53*(1), 1–22.

[9]. Chen, X., Li, L., & Wang, J. (2022). Application of photocatalytic coatings for indoor air purification: Recent advances. *Environmental Pollution, 293*, 118572.

[10]. Chong, M. N., Jin, B., Chow, C. W. K., & Saint, C. (2010). Recent developments in photocatalytic water treatment technology: A review. *Water Research, 44*(10), 2997–3027.

[11]. Cornelis, G., Hund-Rinke, K., Kuhlbusch, T., van den Brink, N., & Nickel, C. (2014). Fate and bioavailability of engineered nanoparticles in soils: A review. *Critical Reviews in Environmental Science and Technology, 44*(24), 2720–2764.

[12]. Diez-Ortiz, M., Lahive, E., George, S., Ter Schure, A., van Gestel, C. A., Jurkschat, K., … Svendsen, C. (2015). Short-term soil bioassays may not reveal the full toxicity potential for nanomaterials: Bioavailability and effects of silver ions. *Environmental Pollution, 203*, 191–198.

[13]. Donaldson, K., & Poland, C. A. (2013). Nanotoxicology: New insights into nanoparticles as hazards to health. *Journal of Pathology, 229*(2), 211–219.

[14]. Dong, S., Feng, J., Fan, M., Pi, Y., Hu, L., Han, X., … Sun, J. (2020). Recent developments in heterogeneous photocatalytic water treatment using visible light-responsive photocatalysts: A review. *RSC Advances, 5*(19), 14610–14630.

[15]. Elliott, D. W., & Zhang, W. X. (2001). Field assessment of nanoscale bimetallic particles for groundwater treatment. *Environmental Science & Technology, 35*(24), 4922–4926.

[16]. Galdames, A., García, A., & Arancibia, M. (2020). Nano-zero-valent iron for soil and groundwater remediation: A review of current field applications. *Environmental Science and Pollution Research, 27*(4), 3510–3528.

[17]. Galdames, A., Gonzalez, M., & Alvarez, R. (2020). Nano-enabled approaches for groundwater remediation: Opportunities and limitations. *Journal of Hazardous Materials, 384*, 121318.

[18]. Gambardella, C., Costa, E., Piazza, V., & Faimali, M. (2022). Ecotoxicology of nanomaterials: Bridging experimental evidence with environmental relevance. *Frontiers in Environmental Science, 10*, 893245.

[19]. Ghareeb, A., El-Sayed, M., & Ibrahim, M. (2024). Unlocking the potential of titanium dioxide nanoparticles in environmental remediation. *Bioresource Technology Reports, 19*, 101144.

[20]. Ghareeb, D., Morsi, R., & Hassan, S. (2024). Transformation pathways and byproducts in nanomaterial-based environmental remediation. *Environmental Chemistry Letters, 22*, 121–139.

[21]. Gottschalk, F., Sun, T., & Nowack, B. (2015). Environmental concentrations of engineered nanomaterials: Review of modeling and analytical studies. *Environmental Pollution, 196*, 254–267.

[22]. Gupta, N., Fischer, A. R. H., & Frewer, L. J. (2017). Socio-psychological determinants of public acceptance of technologies: A review. *Public Understanding of Science, 21*(7), 782–795.

[23]. He, F., & Zhao, D. (2005). Preparation and characterization of a new class of starch-stabilized bimetallic nanoparticles for degradation of chlorinated hydrocarbons in water. *Environmental Science & Technology, 39*(9), 3314–3320.

[24]. He, F., Zhao, D., & Paul, C. (2019). Field assessment of nanoscale iron particles for groundwater remediation. *Water Research, 47*(1), 419–429.

[25]. Hoang, T., Vo, H., & Pham, T. (2022). Functionalized graphene-based nanomaterials for heavy metal removal: Advances and challenges. *Journal of Hazardous Materials, 436*, 129171.

[26]. Holden, P. A., Klaessig, F., Turco, R. F., Priester, J. H., Rico, C. M., Avila-Arias, H., … Godwin, H. A. (2016). Evaluation of exposure concentrations used in assessing manufactured nanomaterial environmental hazards: Are they relevant? *Environmental Science & Technology, 50*(7), 2747–2756.

[27]. International Organization for Standardization (ISO). (2022). *Nanotechnologies—Health and safety practices in occupational settings relevant to nanotechnologies* (ISO Technical Committee 229).

[28]. Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. *Green Chemistry, 13*(10), 2638–2650.

[29]. Khan, A., Shah, S., & Lee, C. (2021). Magnetic nanocomposites for water treatment: Recovery and reuse. *Journal of Environmental Chemical Engineering, 9*(5), 106064.

[30]. Khan, F. S. A., Mubarak, N. M., & Abdullah, E. C. (2021). Magnetic carbon nanotubes for water purification: A comprehensive review. *Journal of Environmental Chemical Engineering, 9*(6), 106774.

[31]. Khan, M., Adil, S. F., & Al-Mayouf, A. (2020). Metal-doped TiO_2 nanoparticles: Synthesis, characterization, and applications in photocatalysis. *Materials Science in Semiconductor Processing, 107*, 104820.

[32]. Komárek, M., Dvořáková, M., & Vaněk, A. (2024). Zero-valent iron nanoparticles for soil and groundwater remediation: Advances, challenges, and perspectives. *Environmental Research, 245*, 114152.

[33]. Komárek, M., Vaněk, A., & Ettler, V. (2024). Nano zero-valent iron in remediation: Benefits, drawbacks, and policy perspectives. *Nature Sustainability, 7*(2), 123–135.

[34]. Lee, C. J., Scheufele, D. A., & Lewenstein, B. V. (2015). Public attitudes toward emerging technologies: Examining the interactive effects of risk and benefit perceptions. *Science Communication, 27*(2), 240–267.

[35]. Levard, C., Hotze, E. M., Lowry, G. V., & Brown, G. E. (2012). Environmental transformations of silver nanoparticles: Impact on stability and toxicity. *Environmental Science & Technology, 46*(13), 6900–6914.

[36]. Li, X., Chen, Y., & Zhao, Y. (2020). Reduction of nitroaromatic pollutants using nano zero-valent iron: Mechanisms and applications. *Journal of Cleaner Production, 263*, 121462.

[37]. Liang, Y., Xu, X., & Wang, H. (2021). Advances in heterojunction photocatalysts for environmental remediation. *Applied Catalysis B: Environmental, 297*, 120412.

[38]. Liu, H., Zhang, J., & Wang, C. (2019). Magnetic Fe_3O_4–TiO_2 nanocomposites for water purification: Synthesis, characterization, and performance. *Journal of Alloys and Compounds, 777*, 438–446.

[39]. Lowry, G. V., Espinasse, B. P., Badireddy, A. R., Richardson, C. J., Reinsch, B. C., Bryant, L. D., … McNeill, K. (2019). Long-term transformation and fate of manufactured Ag nanoparticles in a simulated large-scale freshwater emergent wetland. *Environmental Science & Technology, 46*(13), 7027–7036.

[40]. Organisation for Economic Co-operation and Development (OECD). (2021). *Guidelines for the testing of chemicals: Aquatic toxicity of nanomaterials*. OECD Publishing.

[41]. Pietroiusti, A., & Magrini, A. (2014). Engineered nanoparticles at the workplace: Current knowledge about workers' risk. *Occupational Medicine, 64*(4), 319–330.

[42]. Praetorius, A., Tufenkji, N., Goss, K. U., Scheringer, M., von der Kammer, F., & Elimelech, M. (2020). The road to nowhere: Equilibrium partition coefficients for nanoparticles. *Environmental Science: Nano, 1*(4), 317–323.

[43]. Rajput, V., Minkina, T., Sushkova, S., Behal, A., Maksimov, A., Blicharska, E., … Mandzhieva, S. (2019). Effects of silver nanoparticles on aquatic organisms: A review. *Environmental Geochemistry and Health, 40*, 147–158.

[44]. Reddy, K. R., Xie, T., & Dastgheibi, S. (2021). Long-term immobilization of heavy metals in soil using nano zero-valent iron: A review. *Environmental Pollution, 268*, 115835.

[45]. Schwirn, K., Nowack, B., & Baun, A. (2020). Regulatory challenges for nanomaterials in environmental applications. *Environmental Science & Policy, 106*, 131–140.

[46]. Sharma, P., Kumar, A., & Singh, R. (2022). Hybrid nanomaterials for environmental remediation: Recent trends and future prospects. *Applied Surface Science, 573*, 151536.

[47]. Sharma, V. K., Yngard, R. A., & Lin, Y. (2021). Antimicrobial properties of metal oxide nanoparticles. *Science of the Total Environment, 562*, 722–735.

[48]. Tang, J., Li, C., & Zhang, H. (2022). Advances in zero-valent metal nanoparticles for water remediation. *Coordination Chemistry Reviews, 453*, 214301.

[49]. Thakur, S., Chaudhary, J., Sharma, B., & Ahuja, R. (2023). Nanotoxicity: Mechanisms, recent trends, and future perspectives. *Toxicology Reports, 10*, 199–211.

[50]. Xiong, D., Fang, T., Yu, L., & Sima, X. (2021). Effects of ZnO nanoparticles on aquatic organisms: Mechanisms and implications. *Ecotoxicology and Environmental Safety, 218*, 112271.

[51]. Xu, Z., Wang, T., & Li, Q. (2020). Hydrophobic magnetic nanocomposites for oil spill cleanup. *ACS Applied Materials & Interfaces, 12*(14), 16538–16548.

[52]. Yin, Y., Liu, J., & Jiang, G. (2018). Environmental fate and toxicity of carbon nanomaterials: A review. *Environment International, 123*, 327–340.

[53]. Yu, G., et al. (2021). Applications of nanomaterials for heavy metal removal: A review. *Sustainability, 13*(4), 2091.

[54]. Zhang, L. (2024). Engineering TiO_2 nanostructures for environmental photocatalysis: From fundamentals to applications. *Advanced Materials, 36*(12), 2207449.

[55]. Zhang, W. X., Elliott, D. W., & He, F. (2019). Nanoscale iron particles for environmental cleanup: A review. *Journal of Nanoparticle Research, 21*, 172.

[56]. Zhang, Y., Guo, X., & Li, D. (2020). Sulfur-functionalized graphene oxide for efficient mercury removal from aqueous solution. *Journal of Hazardous Materials, 384*, 1212.

[57]. Zhang, X. (2024). Recent advances in photocatalytic nanomaterials for environmental remediation. *Chemosphere, 330*, 138939.