International Journal of Chemical Science and Research

www.ijcsrjournal.com

Volume - 01
Issue - 02
Month - July
Year - 2026

RECENT ADVANCES IN NANOMATERIALS FOR ENVIRONMENTAL REMEDIATION AND WATER PURIFICATION: A REVIEW

Haekwan Jeon

Department of Materials Science and Engineering,Seoul National University, Seoul 08826, Korea

Received:- 12/06/2026 , Revised:- 13/07/2026 , Accepted:- 20/07/2026 , Published:- 27/07/2026

ABSTRACT

The increasing deterioration of environmental quality and the growing scarcity of clean water have intensified the demand for advanced and sustainable remediation technologies. Nanomaterials have emerged as highly effective materials for environmental remediation because of their exceptional surface area, tunable physicochemical properties, catalytic activity, and multifunctional performance. This review provides a comprehensive overview of recent advances in nanomaterials for water purification and environmental cleanup, focusing on carbon-based nanomaterials, metal and metal oxide nanoparticles, magnetic nanomaterials, nanocomposites, nanomembranes, and smart functionalized materials. Their classification, pollutant removal mechanisms, and applications in eliminating heavy metals, dyes, pharmaceuticals, organic pollutants, and emerging contaminants are discussed. The review also examines current challenges related to nanotoxicity, environmental sustainability, commercialization, and large-scale implementation while highlighting the importance of green synthesis, material recyclability, and circular economy approaches. Overall, nanotechnology presents significant opportunities for developing efficient, sustainable, and next-generation water treatment systems that can effectively address global environmental pollution and water security challenges.

KEYWORDS

Nanomaterials; Environmental remediation; Water purification; Nanotechnology; Sustainable wastewater treatment

1. INTRODUCTION

Rapid industrialization, urbanization, population growth, and intensive agriculture have degraded the environment, polluted water bodies, and resulted in a massive decline in water quality globally. There is a growing list of contaminants in freshwater systems, such as toxic heavy metals and synthetic dyes, pharmaceutical residues, pesticides, petroleum hydrocarbons, per- and polyfluoroalkyl substances (PFAS), and microplastics. These contaminants are highly persistent, highly toxic, and highly mobile and are more difficult to remove with traditional treatment methods. The demand for clean water has been steadily rising, and coupled with the degraded quality of freshwater, the need for more sophisticated and environmentally friendly solutions to contend with the conventional and emerging pollutants has increased (Savage & Diallo, 2005; Khin et al., 2012; Saleem & Zaidi, 2020).

1.1 Global Environmental Pollution and Water Scarcity

Water pollution is one of the most imminent environmental issues of the 21st century. Rivers, lakes, and groundwater are continuously contaminated by effluents from different industrial processes like mining, textiles, production of pharmaceuticals, processing of petrochemicals, and agricultural runoff. Heavy metals such as lead, cadmium, mercury, chromium, and arsenic are not biodegradable and pose serious ecological and human health problems when added to water. Likewise, synthetic dyes from the textile industries reduce light penetration of aquatic ecosystems and form toxic degradation products. Pharmaceutical residues and pesticides are emerging as contaminants because of their persistent and low-level concentrations (Das et al., 2015; Ghasemzadeh et al., 2014). There has been a significant amount of research on emerging pollutants such as PFAS and microplastics in recent years, because of their high environmental persistence and resistance to traditional pollutant removal technologies. Microplastics can carry toxic chemicals and pathogens and can pose an ecological risk, although PFAS have carbon–fluorine bonds which are difficult to break. Water quality is further degraded by oil spills and other chemicals and materials derived from petroleum, which cause disruption of aquatic habitats and inadequate oxygen in the water. With all these pollution sources combined, the water scarcity problem is not just about the water quantity being limited but also the quality of water being affected as well, highlighting the need for innovative solutions in water pollution mitigation (Lee et al., 2017; Saleem & Zaidi, 2020; Wirtu et al., 2025).

1.2 Evolution of Nanotechnology for Environmental Applications

The unique physicochemical properties of nanomaterials have made nanotechnology an emerging area of research for environmental remediation. Applications of engineered nanoparticles in adsorption of pollutants, catalytic degradation, membrane filtration, antimicrobial treatment, and water purification have been studied since the early development of engineered nanoparticles. The synthesis techniques are continuously being improved, and carbon-based nanomaterials, metal nanoparticles, metal oxide nanomaterials, magnetic nanostructures, and multifunctional nanocomposites with superior environmental performances are now being produced (Khin et al., 2012; Guerra et al., 2018). The high remediation efficiency of nanomaterials is mainly due to their small size, extremely high specific surface area, number of surface reaction sites, tunable surface chemistry, and high catalytic activity. These properties make them highly effective for fast adsorption, effective electron transfer, photocatalytic degradation of contaminants, and selective interaction with different contaminants. Many nanomaterials are surface-functionalized for greater selectivity, easily regenerated for reuse, and can be incorporated into hybrid treatment systems, which leads to an increase in the efficiency of the treatment process and a decrease in treatment costs, as compared to traditional adsorbents. The use of nanotechnology to solve complex environmental remediation problems has been further expanded with recent developments in smart nanomaterials, magnetic nanocomposites, and functionalized membranes (Baby et al., 2019; Kumar et al., 2021; Singh, 2022).

1.3 Scope and Objectives of the Review

It is important to consider the evolution of nanotechnology and the complexity of the pollutants in the environment to warrant a comprehensive evaluation of the recent developments. This review thus highlights the recent developments in the use of nanomaterials for environmental cleanup and water purification processes and their classification, physicochemical properties, mechanisms of pollutant removal, and practical applications in the environment. The remediation of contaminations like heavy metals, organic pollutants, dyes, pharmaceutical compounds, oil contaminants, and emerging pollutants using advanced technologies and nanomaterials is particularly emphasised. Moreover, the review addresses existing problems such as the toxicity of nanoparticles, environmental safety, piloting, and recycling of materials, and suggests potential areas of nanoremediation research for the future, which would enable the creation of safer, more efficient, and commercially viable nanoremediation systems. The following sections thoroughly explore the various types of nanomaterials, their remediation mechanisms, the latest technological advancements, environmental applications, sustainability concerns, and outlook for future research in this rapidly evolving field (Del Prado-Audelo et al., 2021; Roy et al., 2021; Aslam et al., 2025).

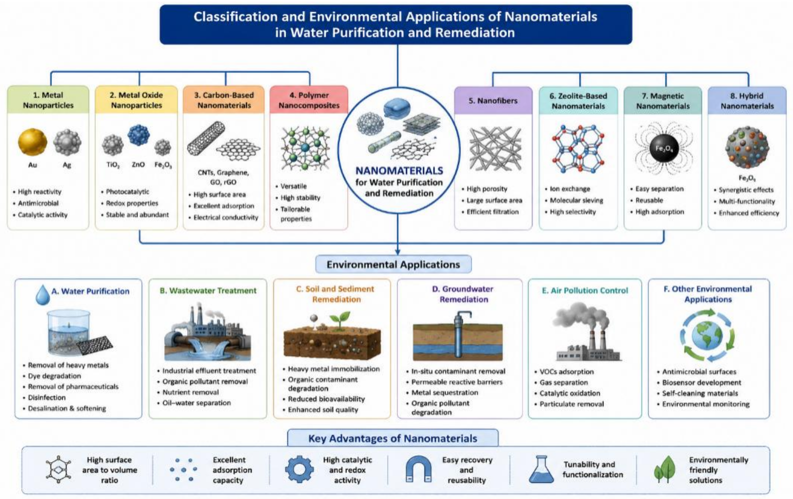

Figure 1. Classification and environmental applications of nanomaterials in water purification and remediation

Figure 1 shows the principal classes of nanomaterials, which are classified into carbon, metal, metal oxide, magnetic, polymeric and hybrid nanomaterials and their major environmental applications including adsorption, photocatalysis, membrane filtration, antimicrobial treatment, oil–water separation and wastewater remediation.

2. ENVIRONMENTAL REMEDIATION VIA NANOMATERIALS: CLASSIFICATION, PROPERTIES AND REMOVAL MECHANISMS

Nanomaterials have transformed the field of environmental remediation with the ability to remove a wide range of contaminants from water, soil and air in an efficient, selective and sustainable manner. The exceptionally good performance of these is mainly due to their nanoscale size, high surface-to-volume ratio, tunable surface chemistry, and multifunctional physicochemical properties. During the last 20 years, many different types of nanomaterials have been developed that can adsorb, degrade, transform, and separate pollutants in a variety of remediation processes. For environmental applications to be used, the classification, functional properties, and removal mechanisms of these nanomaterials are important and desirable to understand to select the most appropriate material for each application (Khin et al., 2012; Guerra et al., 2018).

2.1 Classification of Nanomaterials

Environmental remediation nanomaterials can be categorized by composition and/or purpose. Silver, gold, copper, and palladium nanoparticles have excellent catalytic and antimicrobial properties and can be used to catalyse the degradation of organic pollutants and to disinfect contaminated water. They are highly reactive and may be susceptible to fast oxidation–reduction reactions, but it is also important to consider their stability and recoverability (Ghasemzadeh et al., 2014). Among all, metal oxide nanoparticles have been shown to have exceptional photocatalytic activity, chemical stability, and low cost, and have been the subject of considerable attention. The nanoparticles of titanium dioxide (TiO_2), zinc oxide (ZnO), iron oxides (Fe_3O_4 and Fe_2O_3), manganese oxide, and copper oxide are subjected to extensive research to study the photocatalytic and adsorption processes for the removal of dyes, pharmaceuticals, pesticides, and heavy metals, respectively (Saleem & Zaidi, 2020; Aslam et al., 2025). Carbon-based nanomaterials (CNTs, graphene, GONs, rGO, activated carbon nanostructures, and carbon quantum dots) have a very high specific surface area and number of active sites. These materials have excellent mechanical strength and electrical conductivity (Jatoi et al., 2025), and they are very efficient in the uptake of heavy metals, organic pollutants, antibiotics, and emerging contaminants (Baby et al., 2019). Other possibilities include polymer nanocomposites, electrospun nanofibers, zeolite-based nanomaterials, magnetic nanoparticles, and hybrid nanocomposites. The excellent ion exchange capacity of zeolites, pollutant selectivity of polymer nanocomposites, high pore volume of nanofibers used as a filter, easy remediation following treatment using magnetic nanomaterials, and high remediation efficiency using hybrid nanomaterials (Kumar et al., 2021;

Wirtu et al., 2025).

2.2 Physicochemical Properties Governing Remediation Performance

A few physicochemical properties of nanomaterials will determine the environmental performance of such materials. Conventional adsorbents have lower specific surface area, resulting in fewer adsorption sites. The large specific surface area allows for more adsorption sites than traditional adsorbents. Surface functional groups (hydroxyl, carboxyl, and amino) increase electrostatic attraction, hydrogen bonding, and complexation with metal ions and organic molecules. The catalytic activity allows the degradation of persistent contaminants through photocatalytic and oxidation–reduction reactions, while the electrical conductivity allows the transfer of electrons in the catalytic reaction, especially in the case of graphene-based materials. Further, magnetic properties facilitate the recovery and reuse of magnetic nanoparticles, decreasing secondary pollution, and mechanical stability provides structural strength, allowing for repeated treatment cycles (Savage & Diallo, 2005; Singh, 2022; Roy et al., 2021).

2.3 Mechanisms of Pollutant Removal

Depending on their composition and the pollutants they are used for, nanomaterials take in pollutants in several complementary ways. Taking advantage of the large surface area and reactive functional groups of nanomaterials, the most commonly used mechanism for capturing heavy metals, dyes, pharmaceuticals, and pesticides is adsorption. Under illumination, photocatalysis produces reactive oxygen species (e.g., TiO_2 and ZnO nanoparticles) that cause organic contaminants to be degraded to less harmful products. Reduction–oxidation reactions are helpful to convert toxic substances to less hazardous forms, and ion exchange is helpful to remove dissolved metal ions with zeolite-based materials. Nanofiltration membranes are used in membrane-based systems, which physically remove contaminants from the water with minimal loss of water permeability. Additionally, the catalytic degradation process facilitates the degradation of recalcitrant pollutants, and the magnetic separation process allows the effective recycling of the magnetic adsorbent following pollutant removal, thus enhancing operational sustainability (Del Prado-Audelo et al., 2021; Thirumalaisamy et al., 2022).

2.4 Factors Affecting Remediation Efficiency

Nanomaterials have a significant dependence on operational and environmental parameters concerning remediation efficiency. The pH of the solution impacts the speciation of contaminants and the charge on the surface of the nanomaterials and thus can impact the adsorption capacity. The rate of reactions and the rate of diffusion of reactants are affected by temperature. The rate of a reaction is affected by the available surface area and the catalytic activity of the particles. Chemical functionalization of the surface can markedly enhance selectivity to certain pollutants. The simultaneous co-existence of other contaminants, however, can compete for the active sites, thus lowering the efficiency of the removal. Lastly, sustainability and cost-effectiveness of nanomaterials are crucial to applications, with the ability to regenerate used materials reducing operational costs and secondary waste output (Ethaib et al., 2022; Durgalakshmi et al., 2019).

Table 1. Classification of nanomaterials, physicochemical properties, remediation mechanisms, and major environmental applications

Nanomaterial Class	Key Properties	Primary Removal Mechanism	Major Environmental Applications
Metal nanoparticles	High catalytic activity, antimicrobial properties	Redox reactions, catalytic degradation	Water disinfection, degradation of organic pollutants
Metal oxide nanoparticles	Photocatalytic activity, chemical stability	Photocatalysis, adsorption	Dye degradation, heavy metal removal, wastewater treatment
Carbon-based nanomaterials	High surface area, electrical conductivity	Adsorption, catalytic degradation	Heavy metal adsorption, pharmaceutical and dye removal
Polymer nanocomposites	Mechanical stability, tunable functionality	Adsorption, membrane filtration	Water purification, contaminant separation
Nanofibers	High porosity, large surface area	Membrane filtration	Water and wastewater filtration
Zeolite-based nanomaterials	High ion-exchange capacity	Ion exchange, adsorption	Heavy metal and ammonium removal
Magnetic nanomaterials	Magnetic recoverability, high reactivity	Adsorption, magnetic separation	Reusable wastewater treatment systems
Hybrid nanomaterials	Multifunctionality, enhanced stability	Combined adsorption, photocatalysis, catalysis	Multi-pollutant environmental remediation

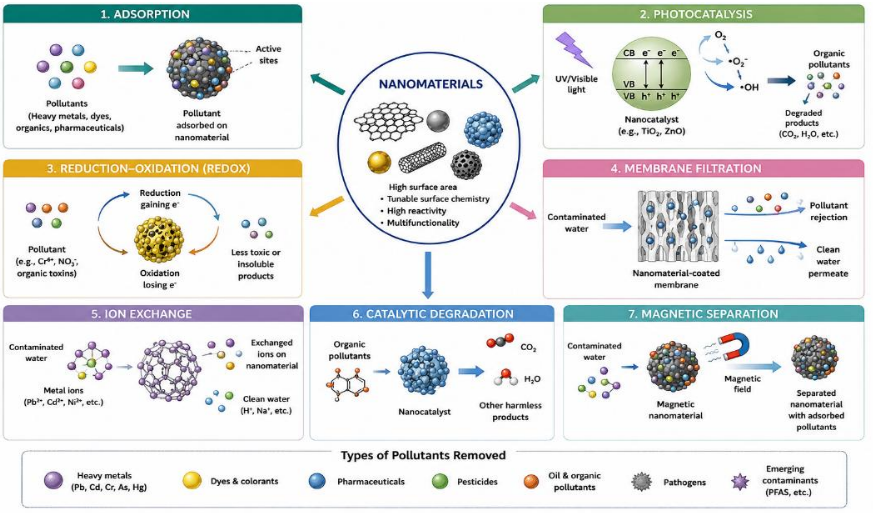

Figure 2. Illustration of pollutant removal mechanisms by nanomaterials

The main mechanisms of nanomaterial-assisted remediation for efficient removal of various environmental contaminants are illustrated in Figure 2, and they are adsorption, photocatalytic degradation, oxidation–reduction reactions, ion exchange, membrane filtration, catalytic degradation, and magnetic separation.

3. RECENT ADVANCES IN NANOMATERIALS FOR WATER PURIFICATION AND ENVIRONMENTAL CLEANUP

The recent advancements in nanotechnology have completely revolutionised environmental remediation with the incorporation of multifunctional nanomaterials to solve the ever increasingly complex problems of water pollution. The adsorption and catalytic properties of modern nanomaterials are significantly improved in terms of capacity, selectivity, stability, or reusability, and this capacity can effectively remove conventional and emerging contaminants. With the developments in the synthesis of new materials, surface functionalization, and hybrid nanostructure design, the removal efficiency of pollutants has been further enhanced, resulting in a more cost-effective and environmentally friendly operation. The innovations have broadened the scope of nanotechnology from laboratory-level investigations to pilot-level water treatment systems, marking its increasing involvement in the sustainable management of the environment (Kumar et al., 2021; Aslam et al., 2025).

3.1 Carbon-Based Nanomaterials

Carbon-based nanomaterials are still the most widely studied adsorbents due to their very high surface area, chemical stability, electrical conductivity, and many active adsorption sites. Carbon nanotubes (CNTs) have hollow tubular structures that are capable of rapid adsorption of heavy metals like lead, cadmium, chromium, and arsenic by electrostatic attraction and surface complexation. The attractive interaction of toxic metal ions and organic pollutants with the surfaces of CNTs is further improved by functionalization of CNT surfaces with oxygen-containing groups (Baby et al., 2019). Graphene and its derivatives are extremely strong and suitable due to their 2-D architecture. Single-layer graphene has a huge surface area that can capture dyes, pesticides, pharmaceuticals, and persistent organic pollutants. Graphene oxide (GO), as one of the graphene derivatives, has a high number of hydroxyl, epoxy, and carboxyl groups, which enhance the hydrophilicity and the strong interaction with the dissolved contaminants. Reduced graphene oxide (rGO), due to its high electrical conductivity and structural stability, is an excellent choice for photocatalytic and electrochemical water treatment systems (Saleem & Zaidi, 2020; Jatoi et al., 2025). Another significant development is activated carbon nanocomposites, combining traditional activated carbon materials with nanoscale metal oxides or graphene-related materials. These composites have superior adsorption characteristics, better regeneration ability, and fouling resistance compared to conventional activated carbon. Carbon-based nanomaterials have been used in the removal of heavy metals, pharmaceutical residues, endocrine-disrupting compounds, pesticides, antibiotics, and emerging contaminants with excellent performance, rendering them versatile materials for new water purification technologies (Baby et al., 2019; Roy et al., 2021).

3.2 Metal and Metal Oxide Nanomaterials

Metal oxide nanoparticles still dominate environmental remediation research because of their high catalytic efficiency and chemical stability. Under ultraviolet or modified visible light illumination, titanium dioxide (TiO_2) is still the best photocatalyst for dye, pesticide, and pharmaceutical residue degradation and the degradation of many organic contaminants. As a result of the generation of ROS, pollutants can be effectively mineralized to the most environmentally friendly products (Guerra et al., 2018). Likewise, zinc oxide (ZnO) nanoparticles have been found to have high photocatalytic and antimicrobial properties and low production costs. In water treatment, ZnO is a good decoloring agent of synthetic dyes and an inhibitor of microbial growth. The nanoparticles of iron oxides, such as Fe_2O_3 and Fe_3O_4, possess both adsorption and magnetic recoverability properties, which makes them highly interesting for the removal of heavy metal ions and for the remediation of contaminated wastewater. They have magnetic characteristics, which make it easy to separate them after treatment, without producing secondary sludge (Ethaib et al., 2022). Metal nanoparticles like silver (Ag) are known to exhibit wide-spectrum antimicrobial action and can disrupt microbial cell membranes and inhibit intracellular metabolic processes to enhance the disinfection of drinking water. Copper oxide (CuO) nanoparticles have dual adsorption and photocatalytic properties for the degradation of organic pollutants, and manganese dioxide (MnO_2) has photocatalytic properties in addition to its ability to oxidize dissolved contaminants and to adsorb heavy metals. The synergistic integration of these nanomaterials into composite systems has significantly enhanced the photocatalytic efficiency, contaminant selectivity, and real wastewater operational stability (Singh, 2022; Aslam et al., 2025).

3.3 Magnetic Nanomaterials

The recovery of materials after the removal of pollutants is simplified by magnetic nanomaterials, which have been of increasing interest. Together with their good adsorption ability, magnetic iron oxide nanoparticles, especially Fe_3O_4, can be separated easily from the medium with their magnetic property, which does not require a complicated filtration or centrifugation process. Once the contaminant is adsorbed, external magnetic fields can be used to recover and regenerate the nanoparticles to use them in subsequent treatment cycles. This property is a major factor in lowering operating costs and secondary environmental pollution. Thus, magnetic nanomaterials are gaining popularity in water treatment facilities for the removal of heavy metals, dyes, antibiotics, oil contaminants, and to make the process more sustainable (Del Prado-Audelo et al., 2021; Kumar et al., 2021).

3.4 Nanocomposite and Hybrid Nanomaterials

In recent years, researchers have been increasingly looking for a combination of different functional components of the nanomaterials in the form of nanocomposite and hybrid nanomaterials to address the limitations of individual nanomaterials. The polymer nanocomposites have the properties of enhanced mechanical strength, enhanced chemical stability, and selective adsorption by optimized functional groups. Metal–organic framework (MOF) composites possess a pore structure with extremely high porosity and a tunable pore structure that can selectively capture organic molecules and heavy metals. Bio-inspired nanocomposites, created with environmentally friendly materials and biological templates, have proven to be eco-friendly alternatives with less environmental impact. The combination of the adsorption, photocatalytic, antimicrobial, and magnetic recovery properties of a single nanomaterial platform is one of the most promising future approaches towards developing environmental remediation technologies (Wirtu et al., 2025; Aslam et al., 2025).

3.5 Nanomembranes and Nanofibers

The development of new membrane-based water treatment technologies, such as electrospun nanofiber technology, has significantly improved water treatment technologies using membranes. As a result of the porous interconnected structure, high permeability, and large surface areas of the electrospun nanofibers, they can serve as efficient filters for suspended solids, microorganisms, and dissolved pollutants. The membrane fouling resistance, contaminant rejection, and permeability properties are better for nanofiltration membranes containing nanoparticles. These systems have been tested to attain excellent performance in desalination, industrial wastewater treatment, and oil–water separation applications, and the oil-repellency properties of the modified membranes are excellent for the separation of oil from the water side. This is advantageous to save energy and extend the membrane service life (Lee et al., 2017; Zahid & Abd-Elsalam, 2021).

3.6 Nanomaterials for smart and functional applications

Nanomaterials of the new generation focus on intelligence and sustainability. Chemical functionalization of the surface allows for increased adsorption selectivity towards specific contaminants and increased material stability. These stimuli-responsive nanomaterials can change their physicochemical properties when the pH changes, temperature, magnetic fields, or light. They can be used to control the release and capture of pollutants. Also, self-cleaning nanomaterials use photocatalytic reactions to break down any potential contaminants that build up, thus helping to ensure long-term performance. Multiple recycling cycles can be achieved without substantial loss of efficiency, thus lowering operating expenses and reducing waste generation, for recyclable nanomaterials, such as magnetic and hybrid nanocomposites. Smart multifunctional nanomaterials, green synthesis methods, and environmentally friendly hybrid systems have also been highlighted in recent reviews (published 2024–2025) as critical innovations that may boost the commercialization of nanotechnology-enabled water purification and environmental remediation technologies (Anwar & Baker, 2025; Aslam et al., 2025; Jatoi et al., 2025).

Table 2. Comparison of Recent Nanomaterials for Water Purification and Environmental Remediation

Nanomaterial	Target Pollutants	Primary Removal Mechanism	Major Advantages	Key Limitations
Carbon nanotubes	Heavy metals, dyes, pharmaceuticals	Adsorption	High surface area, rapid adsorption	High production cost
Graphene/Graphene oxide	Organic pollutants, antibiotics, pesticides	Adsorption, photocatalysis	Excellent conductivity, abundant functional groups	Agglomeration tendency
TiO_2 nanoparticles	Organic pollutants, dyes	Photocatalysis	High stability, strong oxidation ability	Limited visible-light activity
ZnO nanoparticles	Dyes, microorganisms	Photocatalysis, antimicrobial activity	Cost-effective, efficient degradation	Photocorrosion under prolonged use
Fe_3O_4 nanoparticles	Heavy metals, dyes	Adsorption, magnetic separation	Easy recovery and regeneration	Surface oxidation
Ag nanoparticles	Pathogenic microorganisms	Antimicrobial action	Broad-spectrum disinfection	Potential nanotoxicity
MOF-based composites	Heavy metals, pharmaceuticals	Adsorption	High porosity and selectivity	Moisture sensitivity in some MOFs
Electrospun nanofibers	Suspended solids, oil, microorganisms	Membrane filtration	High permeability, fouling resistance	Membrane fabrication cost

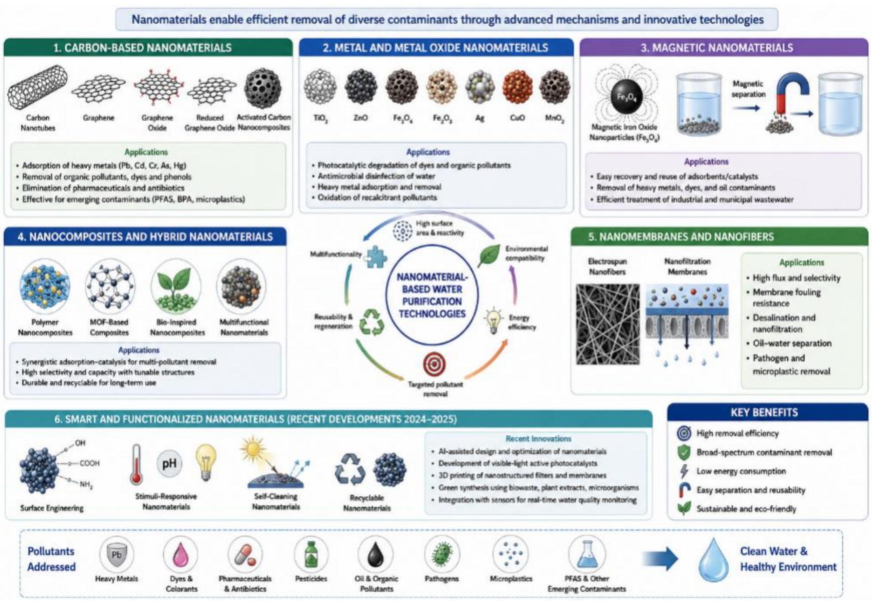

Figure 3. Recent Advances in Nanomaterial-Based Water Purification Technologies

As shown in Figure 3, the recent advancements in water purification using carbon-based, metal oxide, magnetic, hybrid, membrane, and smart nanomaterials are highlighted, with a focus on adsorption, photocatalysis, and antimicrobial treatment, magnetic recovery, desalination, oil–water separation, and recyclable multifunctional remediation systems.

4. ENVIRONMENTAL APPLICATIONS, CHALLENGES & SUSTAINABILITY CONSIDERATIONS

The potential fields of application of nanomaterials have been extended from laboratory research to a wide range of environmental remediation systems, due to the rapid progress in nanotechnology. Because of their great adsorption capacity, catalytic efficiency, and surface properties, they have been used to treat contaminated water, polluted soils, sediments, and polluted atmosphere more effectively than many of the conventional technologies. But, in addition to these technological innovations, issues of environmental safety, nanotoxicity, long-term sustainability, and commercial implementation are growing in significance. Thus, it is important to consider the benefits and possible risks of using nanomaterials in remediation processes to guarantee their responsible and sustainable application (Guerra et al., 2018; Del Prado-Audelo et al., 2021).

4.1 Water and Wastewater Treatment

The demand for safe drinking water and effective treatment of wastewater has led to a wide range of research investigations into water purification applications of nanomaterials. Nanomaterials are extremely effective at removing suspended solids, heavy metals, pathogenic microorganisms, dyes, pharmaceutical residues, pesticides, and emerging contaminants from various water sources. They have high specific surface area, high active sites, and catalytic properties that enable them to quickly remove contaminants and minimise treatment time and chemical usage (Savage & Diallo, 2005; Singh, 2022). Nanomaterials as adsorbents and membranes can remove toxic materials like arsenic, lead, mercury, fluoride, and microbial pollutants from drinking water sources while minimizing water quality changes. High adsorption capacity and antimicrobial activity of carbon nanotubes, graphene derivatives, and metal oxide nanoparticles have been observed for improvement in both chemical and biological water quality. Advanced nanofiltration membranes further improve the process of drinking water treatment by selectively rejecting dissolved contaminants while keeping the water permeability high (Saleem & Zaidi, 2020). Nanomaterials are used extensively in industrial wastewater treatment to remove dyes, petroleum hydrocarbons, pharmaceutical compounds, textile effluents, and heavy metals from industrial wastewater effluents from the mining, electroplating, chemical manufacturing, and textile industries. The photocatalytic use of nanoparticles like TiO_2 and ZnO for the degradation of persistent organic pollutants in the presence of light is effective, and the magnetic particles iron oxide can be used to rapidly absorb the pollutants and then recover them by magnetism, thereby eliminating the generation of secondary waste (Ghasemzadeh et al., 2014; Ethaib et al., 2022). For municipal wastewater, nanotechnology can help in the removal of nutrients, organic matter, microorganisms, and trace contaminants. Nanocomposite membranes enhance filter efficiency, decrease membrane fouling, and help extend filter life. Nanomaterials can be injected into the soil, moving through contaminated groundwater and interacting with pollutants within the aquifer to treat the soil in place. They have the capacity to immobilize toxic metals and also degrade chlorinated organic compounds, which are beneficial to conventional excavation-based remediation works (Wirtu et al., 2025; Roy et al., 2021).

4.2 Soil and Sediment Remediation

Nanotechnology has also proven helpful to mitigate soil and sediment contamination due to industrial processes, mining, and agriculture. High levels of accumulated heavy metals in soils can cause chronic ecological and human health problems due to their long-term persistence and ability to be transferred to food chains. The use of nanomaterials to reduce the mobility of metals, such as through precipitation, surface complexation and adsorption, lowers contaminant bioavailability and does not involve a significant amount of soil excavation (Khin et al., 2012). Nanomaterials enhance the degradation of organic contaminants such as petroleum hydrocarbons, pesticides, chlorinated solvents and polycyclic aromatic hydrocarbons, as well as heavy metal immobilization. The photocatalytic nanomaterials can produce ROS that can convert persistent organic pollutants to less toxic intermediates or mineralization products. The bio-inspired nanocomposites and functionalized nanoparticles further enhance the remediation efficiency by combining catalytic degradation with selective adsorption, which helps to achieve long-term remediation of the contaminated terrestrial environment (Kumar et al., 2021; Thirumalaisamy et al., 2022).

4.3 Air Pollution Control

Water remediation is still the main application field, but there is an increasing interest in using nanomaterials to reduce pollution in the air. Volatile organic compounds (VOCs) from industrial processes, transportation, and chemical manufacturing can be effectively captured by nanostructured adsorbents. Due to their porous nature and their excellent adsorption capacity, they are capable of effective removal of harmful gaseous pollutants with minimum pressure loss during filtration (Das et al., 2015). Nanomaterials can also be used for gas adsorption, selective adsorption, and catalytic conversion of pollutants, e.g., NOx, SOx, CO2, NH3. Metal oxide nanoparticles have high catalytic activity for catalytic oxidation that transforms toxic gases to less hazardous products under relatively mild operating conditions. Aquatic and non-aquatic environments are not the only spaces where nanotechnology can be applied to tackle multiple compartments (KHARISOV et al., 2014; Wirtu et al., 2025).

4.4 Environmental and Human Health Risks

Although nanomaterials are environmentally friendly, their use is widespread and raises concerns about the potential effects that they might have on the health of the environment and humans. The very small size of nanoparticles can allow them to cross biological membranes, lodge in the tissue, and react with tissue components in a manner different from bulk materials. It is important to have a detailed analysis of the nanotoxicity of certain engineered nanoparticles before their widespread use, as they have been linked to oxidative stress, inflammation, and toxicity to cells under certain conditions of exposure (Guerra et al., 2018). The bioaccumulation in aquatic organisms and potential transfer through food chains is another important factor to take into account. Ongoing releases of persistent nanoparticles into natural ecosystems can interact with microorganisms, plants, invertebrates, and fish and may affect the function of the ecosystem. Under complex environmental conditions, the environmental fate and transport of nanomaterials, such as aggregation, dissolution, transformation, and degradation, are not well understood. For this reason, there is a need for standardizing methods for assessing the long-term ecotoxicological impacts of the implementation of remediation systems based on nanotechnology, so that the implementation is environmentally responsible (Saleem & Zaidi, 2020; Del Prado-Audelo et al., 2021).

4.5 Sustainability and Circular Economy

The principles of sustainability and circular economy are becoming more and more relevant for future development of nanotechnology. The green synthesis approaches based on plant extracts, microorganisms, and biodegradable polymers minimize the use of hazardous chemicals and limit the environmental impact involved in the production of nanoparticles. These green synthetic methods contribute to safer production methods and enhanced consumer acceptance (Aslam et al., 2025). Another important sustainability benefit of the reusability of nanomaterials is reusability. In some cases, simple physical or chemical treatments can be used to regenerate magnetic nanoparticles, graphene composites, and hybrid nanomaterials to achieve significant remediation efficiency in a non-destructive manner. The installation of life cycle assessment (LCA) and its application in the development of nanomaterials allows for evaluating the energy consumed, the environmental emissions generated, resource use, and waste produced during the production, application, regeneration, and disposal process. Nanotechnology has a lot of promise in the long term, but there are still some challenges in the area of cost-effectiveness and commercialization on an industrial scale due to synthesis costs, uncertainty about regulations, and limited industrial-scale manufacturing. So, on the way forward, it is worth focusing on scalable production methods, green synthesis, standardized safety assessment, and economically viable production strategies for sustainable implementation in the circular environmental management systems (Durgalakshmi et al., 2019; Kumar et al., 2021; Anwar & Baker, 2025).

Table 3. Advantages, Environmental Concerns, and Sustainability Strategies of Nanomaterials

Aspect	Key Features	Environmental Implications	Sustainability Strategies
Water purification	High adsorption, photocatalysis, antimicrobial activity	Efficient removal of heavy metals, dyes, pharmaceuticals, and pathogens	Regenerable adsorbents, recyclable nanomaterials
Soil and sediment remediation	Immobilization of heavy metals, catalytic degradation of organics	Reduced contaminant mobility and ecological restoration	Green synthesis, reusable nanocomposites
Air pollution control	VOC adsorption, catalytic oxidation, gas separation	Reduction of atmospheric pollutants and toxic emissions	Durable catalysts with long operational life
Environmental concerns	Nanotoxicity, bioaccumulation, ecotoxicity, environmental	Potential risks to aquatic organisms, soil microbes, and human health	Standardized risk assessment, controlled release, environmental monitoring

	persistence		
Circular economy	Material recovery, regeneration, life cycle optimization	Reduced waste generation and resource consumption	Life cycle assessment, scalable green production, cost-effective regeneration

5. FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

5.1 Emerging Research Trends

Developing intelligent, sustainable, and multifunctional materials is expected to be the leading way in which nanotechnology will be used to solve problems of pollution in the future. As a result of industrialization, urbanization, and the development of chronic pollutants, water pollution is becoming a more complex problem, demanding a new generation of nanomaterials that are more selective, stable, and efficient to operate, with a minimal impact on the environment. Advanced research has developed more towards a system wherein multiple functions are placed on a single materials platform; in this case, adsorption, catalysis, sensing, and self-regeneration. One of the most promising developments is smart nanomaterials with external stimulus-responsive dynamic behavior such as pH, temperature, light, magnetic field, and chemical composition. These can be developed to enhance the capability for controlled adsorption and release of pollutants, catalytic activity that can adapt to the surroundings, and performance flexibility under various environmental conditions. This responsive action enables the efficiency of the treatment process, which reduces the quantity of chemicals and energy consumed. Another technology that has become significant in the creation of nanomaterials is artificial intelligence (AI). By leveraging AI in materials design, the properties of materials can be predicted quickly, synthesis conditions can be optimized, and the materials can be tailored to treat contaminants optimally. Much experimental data can be fed into machine learning algorithms to uncover materials in a faster time, reduce lab costs, and predict material performance more accurately. This data-based approach will minimize development time and help design very efficient remediation materials. Another important trend is towards the creation of multifunctional nanocomposites containing several remediation mechanisms in a single system. This hybrid material can remove more than one class of pollutants thanks to its adsorption, photocatalytic, and antimicrobial properties and its magnetic recovery and membrane separation. Multifunctionality is also crucial in the treatment of complex wastewaters, including wastewater containing heavy metals, pharmaceuticals, dyes, pathogens, and emerging wastes. Therefore, a search for an approach towards synthesis that is environmentally friendly is also receiving attention from researchers, as is the basis of green nanotechnology. Utilization of biological resources such as plant extracts, microorganisms, algae, and biodegradable polymers is becoming more and more popular for the production of nanoparticles without the use of harmful chemicals. These methods help to minimize environmental impacts, enhance biocompatibility of materials, and promote sustainable manufacturing processes.

5.2 Commercialization Challenges

Several obstacles still need to be overcome for nanotechnology-based remediation systems to become commercially viable, even though there have been impressive scientific advances. One of the biggest uncertainties is regulatory, as internationally accepted guidelines for the production of nanoparticles, their environmental release, and disposal are still being developed. Clear regulatory frameworks are crucial to both ensure the safety of the environment and public confidence. The other significant drawback is the lack of a standard testing procedure. Comparisons between studies are difficult due to different synthesis techniques, particle characterization, experimental conditions, and performance evaluation. Due to different synthesis techniques, different ways of characterizing the particles, different experimental conditions, and different ways of evaluating the performance, it is difficult to compare from one study to another and even more difficult to validate the technology. The establishment of universally accepted criteria for the efficiency, stability, toxicity, and regeneration of the technology would ease technology transfer between research laboratories and industry. Technical and economic problems are also encountered in large-scale manufacturing. The high-performance nanomaterials usually need complex synthesis methods, costly precursor materials, and processing conditions, which lead to high production costs. In addition, it is hard to stabilize the quality of the material in mass production. Scalable synthesis routes with high performance and economic feasibility will be key to future commercialization. Another key focus of the program is cost reduction. While nanomaterials can show remediation efficiency that is better than conventional materials, their widespread use should be possible using low-cost manufacturing methods, easy regeneration, and long lifespan. Improving recyclability and minimising losses of materials in successive treatment cycles will significantly boost overall economic viability.

5.3 FUTURE OUTLOOK

Nanotechnology will play an important role in the environmental remediation technologies of the future, combined with other complementary technologies, to be more efficient and sustainable. The combination of nanomaterials and advanced oxidation processes, membrane filtration, biological treatment, and electrochemical systems will yield a synergistic effect for better degradation of contaminants and lower energy use. Pollutant mixtures seen in real wastewater systems are growing in complexity and challenge, and such integrated treatment platforms are expected to be able to handle them. The principles of the circular economy will be increasingly used in the development of nanomaterials. The use of recyclable adsorbents, regenerable catalysts, recuperation of resources from wastewater, and environmentally friendly production methods will be instrumental in reducing waste emissions and optimizing materials. Development of longer-lasting nanomaterials, which are easier to regenerate, will further improve sustainability. Future water purification systems will be decentralized, efficient, and flexible to local environmental conditions. Nanotechnology-based treatment systems could offer access to clean drinking water in remote communities, disaster-stricken areas, and water-limited areas. At the same time, intelligent monitoring systems coupled with sensors and automated process control will lead to the optimization of treatment performance in real time. Future studies should focus on detailed environmental risk assessment, long-term stability evaluation, large-scale field demonstration, and life cycle analysis to ensure safe implementation. The need to bridge the gaps between interdisciplinary research and practical technology will necessitate greater interdisciplinary collaboration among materials scientists, environmental engineers, toxicologists, policymakers, and industry partners. Incorporating technological innovation, sustainability principles, and responsible governance, nanotechnology holds the promise of playing a pivotal role in environmental remediation and ensuring water security in the future.

6. CONCLUSION

Nanotechnology has become one of the most promising techniques that are employed for addressing the contemporary problems of pollution and increasing water demands. Appearance and development of engineered nanomaterials (ENMs) have significantly improved the efficiency of contaminant removal due to their high adsorption capacity, catalytic capacity, high surface reactivity, and multi-functionality in contaminant removal. In recent years, applications of carbon-based nanomaterials, metal and metal oxide nanoparticles, magnetic nanomaterials, nanocomposites, nanofibers, and smart hybrid systems have been expanded to remediation of heavy metals, dyes, pharmaceutical residues, pesticides, oil contaminants, and other emerging pollutants. The innovations have demonstrated great potential in improving water treatment methods and fostering sustainable and effective environmental management practices. The main findings of this review are that the effect of nanomaterials is dependent on their physicochemical properties, surface functionalization, the materials used for regeneration, and incorporation with advanced treatment technologies. Besides the above, the development of multi-functional and recyclable nanomaterials has increased the efficiency of pollutant removal and decreased the operational costs and material consumption. Furthermore, the recent development of green synthesis and smart design of nanomaterials underscores the growing emphasis on sustainable and resource-efficient methods for remediation applications. All of these achievements have been achieved, but some issues have been identified that will slow the progress of nanotechnology applications in environmental applications. The potential of nanotoxicity, environmental persistence, large-scale manufacturing, regulatory considerations, and economic viability need to be explored before large-scale commercialization. To enable safe and reliable applications, standardised evaluation procedures will have to be developed, and the long-term material stability will have to be enhanced, as well as thorough environmental risk assessments to be carried out. Nanotechnology is a novel technology platform for sustainable environmental remediation and water purification in general. Ongoing development of materials, green manufacturing, intelligent system design, and interdisciplinary research, etc. are expected to further solve the current problems and speed up the practical application. Developed responsibly and regulated, next-generation nanomaterials can provide effective solutions that are scalable and environmentally friendly for managing water resources and water pollution, contributing to water security and an environmentally sustainable future on a global scale.

REFERENCES:

1. Anwar, A., & Baker, S. (2025). Environmental Applications of Nanoparticles: Water Purification and Pollution Control. Nanoscale Reports, 8(2), 1-4.
2. Aslam, H., Ali, A., Umar, A., Khan, M. U., Azam, M. Z., Ullah, H., ... & Rahman, M. M. (2025). Smart nanomaterials for clean water and a comprehensive exploration of the potentials of metal oxide nanoparticles in environmental remediation. Zeitschrift für Physikalische Chemie.

3. Baby, R., Saifullah, B., & Hussein, M. Z. (2019). Carbon nanomaterials for the treatment of heavy metal-contaminated water and environmental remediation. Nanoscale research letters, 14(1), 341.
4. Das, S., Sen, B., & Debnath, N. (2015). Recent trends in nanomaterials applications in environmental monitoring and remediation. Environmental Science and Pollution Research, 22(23), 18333-18344.
5. Del Prado-Audelo, M. L., García Kerdan, I., Escutia-Guadarrama, L., Reyna-González, J. M., Magaña, J. J., & Leyva-Gómez, G. (2021). Nanoremediation: nanomaterials and nanotechnologies for environmental cleanup. Frontiers in Environmental Science, 9, 793765.
6. Durgalakshmi, D., Rajendran, S., & Naushad, M. (2019). Current role of nanomaterials in environmental remediation. In Advanced nanostructured materials for environmental remediation (pp. 1-20). Cham: Springer International Publishing.
7. Ethaib, S., Al-Qutaifia, S., Al-Ansari, N., & Zubaidi, S. L. (2022). Function of nanomaterials in removing heavy metals for water and wastewater remediation: A review. Environments, 9(10), 123.
8. Ghasemzadeh, G., Momenpour, M., Omidi, F., Hosseini, M. R., Ahani, M., & Barzegari, A. (2014). Applications of nanomaterials in water treatment and environmental remediation. Frontiers of environmental science & engineering, 8(4), 471-482.
9. Guerra, F. D., Attia, M. F., Whitehead, D. C., & Alexis, F. (2018). Nanotechnology for environmental remediation: materials and applications. Molecules, 23(7), 1760.
10. Jatoi, A. S., Ahmed, J., Bhutto, A. A., & Jeyapaul, A. S. (2025). Recent advances and future perspectives of carbon-based nanomaterials for environmental remediation. Brazilian Journal of Chemical Engineering, 42(1), 151-169.
11. KHARISOV, B. I., KHARISSOVA, O. V., & DIAS, H. R. (2014). Nanomaterials for Environmental Protection.
12. Khin, M. M., Nair, A. S., Babu, V. J., Murugan, R., & Ramakrishna, S. (2012). A review on nanomaterials for environmental remediation. Energy & Environmental Science, 5(8), 8075-8109.
13. Kumar, L., Ragunathan, V., Chugh, M., & Bharadvaja, N. (2021). Nanomaterials for remediation of contaminants: a review. Environmental Chemistry Letters, 19(4), 3139-3163.
14. Lee, C. H., Tiwari, B., Zhang, D., & Yap, Y. K. (2017). Water purification: oil–water separation by nanotechnology and environmental concerns. Environmental Science: Nano, 4(3), 514-525.
15. Roy, A., Sharma, A., Yadav, S., Jule, L. T., & Krishnaraj, R. (2021). Nanomaterials for remediation of environmental pollutants. Bioinorganic Chemistry and Applications, 2021(1), 1764647.
16. Saleem, H., & Zaidi, S. J. (2020). Developments in the application of nanomaterials for water treatment and their impact on the environment. Nanomaterials, 10(9), 1764.
17. Savage, N., & Diallo, M. S. (2005). Nanomaterials and water purification: opportunities and challenges. Journal of Nanoparticle research, 7(4), 331-342.
18. Singh, K. K. (2022). Role of nanotechnology and nanomaterials for water treatment and environmental remediation. International Journal of New Chemistry, 9(3), 165-190.
19. Thirumalaisamy, R., Suriyaprabha, R., Prabhu, M., & Thesai, A. S. (2022). Role of nanomaterials in environmental remediation: recent advances—a review. Strategies and Tools for Pollutant Mitigation: Research Trends in Developing Nations, 51-68.
20. Wirtu, S. F., Jule, L. T., & Nagaraj, N. (2025). Nanomaterials for environmental applications: water treatment, air purification, and remediation. In Exploring Nanomaterial Synthesis, Characterization, and Applications (pp. 489-514). IGI Global Scientific Publishing.
21. Zahid, M., & Abd-Elsalam, K. A. (2021). Applications of nanomaterials in water remediation: A note from the Editors. In Aquananotechnology (pp. 1-10). Elsevier.