

Applications of Nanomaterials in Environmental Remediation

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Abstract. A key challenge in environmental pollution remediation is the diversity of pollutants, which vary greatly in sources, physicochemical properties, and migration behaviors. Consequently, conventional single-treatment technologies often cannot efficiently tackle complex pollution problems. In recent years, continuous technological advances have made nanomaterials a major research focus in environmental protection, owing to their unique microstructures and interfacial reaction capabilities. Recent studies have demonstrated that nanomaterials can significantly improve pollutant removal efficiency and perform distinct roles depending on the pollutant type. For instance, in heavy metal remediation, nanomaterials are primarily employed for pollutant immobilization and transformation, whereas in treating organic pollutants, they are more commonly used to promote degradation. Meanwhile, differences among environmental media, including water, air, and soil, can influence the performance of nanomaterials. Current research indicates that nanomaterials hold promise for environmental remediation. However, their stability, environmental safety, and practical performance still require further validation and assessment. Future studies should place greater emphasis on elucidating the relationships between material properties and environmental conditions, thereby providing theoretical support for the advancement of environmental remediation technologies.

Keywords: Nanomaterials, Environmental Remediation, Pollutant Removal, Heavy Metal Contamination, Organic Pollutants, Environmental Management

1. Introduction

As industrialization and urbanization advance rapidly, large amounts of industrial waste, exhaust emissions, and municipal solid waste have been released into the environment, causing increasingly severe pollution in water, soil, and air. Environmental pollutants are highly diverse, among which heavy metal ions and organic pollutants have drawn particular concern due to their high toxicity, persistence, and potential for accumulation through food chains, thereby exacerbating pollution hazards and posing long-term threats to ecosystem stability and human health [1].

Due to the high stability of these emerging pollutants, conventional remediation methods are often ineffective. Consequently, developing efficient treatment technologies has become a major research focus. In recent years, both domestic and international scholars have conducted extensive studies on applying nanomaterials in environmental remediation. For example, researchers reported

that nanomaterials possess superior adsorption capacity and catalytic degradation efficiency compared with conventional materials due to their large specific surface area and abundant active surface sites. Liu et al. demonstrated that the emergence of novel pollutants, such as antibiotics and microplastics, has increased the complexity of pollutant behavior in the environment, which results in multiphase distribution and coupled migration processes. Traditional remediation technologies are often insufficient to effectively address these challenges, highlighting the need for the development of new materials and technologies [2]. Xu et al. further showed that regulating the structure and surface properties of nanomaterials can significantly enhance their efficiency in removing various pollutants [3].

Drawing on relevant literature published over the past five years, this study systematically reviews the types and mechanisms of nanomaterials used for pollutant removal. This study aims to clarify the mechanistic differences among various nanomaterials and assess their suitability for specific pollution scenarios. The findings of this study may provide valuable references for designing and optimizing nanomaterial structures and performance.

2. Core characteristics of nanomaterials

When the size of materials is reduced to the nanoscale, their physicochemical properties change significantly. These changes are generally closely associated with surface effects and quantum effects. Previous studies have shown that as particle size decreases, the proportion of surface atoms increases substantially, which alters the surface chemical behavior and enhances its reactivity [4]. This characteristic enables nanomaterials to exhibit distinct advantages in adsorption and catalytic processes.

As particle size decreases further, quantum confinement effects become increasingly important. When material size approaches the characteristic scale of electrons, its electronic energy levels change from continuous to discrete states, thereby influencing light absorption and electron transition processes [5]. Quantum size effects can also induce changes in the optical and electrical properties of materials, as widely reported in both metallic and semiconductor nanostructures [6]. Collectively, these effects determine the reaction pathways and efficiencies of nanomaterials during pollutant transformation processes.

3. Common types of nanomaterials and comparison of their applications

Nanomaterials commonly used in environmental remediation are mainly carbon-based materials, semiconductor photocatalysts, metal-based nanomaterials, and metal-organic frameworks (MOFs).

Carbon-based nanomaterials, such as graphene and carbon nanotubes, possess high specific surface areas and abundant π -electron structures. These materials can remove organic pollutants through π - π interactions and electrostatic adsorption, which makes them particularly suitable for treating dyes and certain types of organic wastewater. However, their selectivity toward inorganic ions, such as heavy metals, is relatively weak, and recovering these materials remains challenging in practice.

Semiconductor photocatalytic materials, such as TiO_2 and $\text{g-C}_3\text{N}_4$, generate electron-hole pairs under light irradiation, and these subsequently produce highly oxidative reactive species that degrade organic pollutants. These materials have demonstrated promising performance in the treatment of antibiotic and dye contamination. Nevertheless, their applications are limited by factors such as narrow light-response ranges and high electron-hole recombination rates.

Metal-based nanomaterials, such as nanoscale zero-valent iron (nZVI), remove pollutants through reduction reactions during environmental remediation. They are particularly effective for treating heavy metal ions and halogenated organic compounds. However, these materials tend to oxidize and deactivate during use, and may release secondary metal contaminants.

Metal-organic frameworks (MOFs) perform well in pollutant adsorption and separation owing to their highly tunable pore structures and large specific surface areas. They are especially suitable for removing gaseous pollutants and certain small organic molecules. However, the poor stability of MOFs in aqueous environments limits their long-term application in water treatment.

In practical applications, different types of nanomaterials are often selected according to the properties of the target pollutants. For example, organic dyes are generally more effectively treated using carbon-based materials or photocatalytic materials, whereas heavy metal contamination is more suitably addressed using metal-based reductive materials. This "material–pollutant matching relationship" is a key factor for improving remediation efficiency.

4. Applications of nanomaterials in different environmental media

4.1. Water pollution remediation

Water pollution is a major environmental challenge worldwide. The primary contaminants in aquatic environments include heavy metals and organic pollutants, many of which have high toxicity and are resistant to degradation. Conventional treatment methods, such as adsorption, often exhibit limited effectiveness when dealing with complex pollution scenarios because of their relatively low adsorption capacities and limited reusability. Owing to their large specific surface areas and tunable surface properties, nanomaterials are increasingly applied in water pollution remediation [7].

For heavy metal contamination, metal-based nanomaterials, particularly nanoscale zero-valent iron (nZVI), are widely used. These materials can convert heavy metal ions into insoluble or less toxic forms through reduction reactions. In addition, their surfaces provide abundant adsorption sites, enabling the simultaneous removal of contaminants through both reduction and adsorption mechanisms. However, these materials have drawbacks. In practice, they may oxidize and deactivate, and potentially release secondary contaminants.

Considerable research has also focused on the use of semiconductor photocatalytic materials for the treatment of organic pollutants. Under light irradiation, titanium dioxide (TiO₂) generates electron–hole pairs that are strongly oxidizing. These charge carriers subsequently react with water molecules and oxygen to produce highly reactive species, such as hydroxyl radicals. The generated reactive species can oxidize organic pollutants into harmless products, primarily carbon dioxide and water, thereby achieving pollutant degradation. Furthermore, incorporating graphene into photocatalytic materials can effectively suppress electron–hole recombination and enhance photocatalytic efficiency [8].

Carbon-based nanomaterials are another important class in water treatment, where adsorption is the primary remediation mechanism. Graphene, a representative carbon-based nanomaterial, possesses a high specific surface area and porous structure, making it highly suitable for wastewater treatment applications. Through π – π interactions and electrostatic adsorption, graphene removes a wide range of pollutants, including dyes and antibiotics [9]. Compared with metal-based nanomaterials, carbon-based materials generally have lower risks of secondary contamination while offering relatively simple and efficient treatment processes.

4.2. Air pollution control

Air pollution primarily originates from industrial activities and transportation emissions. Among atmospheric pollutants, VOCs are regarded as a major category. VOCs originate from both natural and anthropogenic sources. Excessive accumulation of anthropogenic VOCs may pose significant risks to human health, and their high volatility can adversely affect air quality. Given their wide distribution in both indoor and outdoor environments, removing VOCs has become a key focus in air pollution control research [10].

The degradation of VOCs is mainly achieved through catalytic oxidation and photocatalytic processes involving nanomaterials. Titanium dioxide (TiO_2) is one of the most widely used photocatalysts. Similar to its application in water treatment, TiO_2 generates electron-hole pairs under light irradiation, leading to the formation of reactive radicals that oxidize VOCs into carbon dioxide and water. Previous studies have indicated that photocatalytic technologies are relatively efficient in treating low-concentration gaseous pollutants [11].

In practice, nanomaterials are often incorporated into composites or fabricated as coatings. The combination of photocatalytic nanomaterials with carbon-based materials can improve charge separation efficiency, thereby enhancing pollutant degradation performance [12]. Integrating nanomaterials into air purification systems enables the continuous degradation of airborne contaminants.

Photocatalytic nanomaterials are highly effective for VOC degradation. However, under complex pollution scenarios involving multiple contaminants, additional treatment approaches are often required. Moreover, the performance of photocatalytic processes remains strongly influenced by environmental conditions, such as light intensity and humidity.

4.3. Soil remediation

Soil pollution mainly results from agriculture and solid waste accumulation. Common forms of contamination include heavy metals and organic pollutants. Compared with water pollution, soil contamination is generally more concealed, harder to degrade, and more likely to enter food chains, which exerts long-term impacts on ecosystems. Consequently, effective soil remediation requires technologies with long-term stability.

For heavy metal contamination, nanomaterials often immobilize pollutants through adsorption and precipitation. Metal oxide nanomaterials convert heavy metals into more stable forms through adsorption and precipitation processes, thereby immobilizing contaminants in soil. This process significantly reduces pollutant bioavailability and mobility, ultimately mitigating their adverse effects on living organisms [13].

For organic pollutants, nanomaterials generally promote degradation reactions. For example, in PAH-contaminated soils, nanomaterials can enhance remediation by increasing pollutant-active site contact [14]. Studies have further demonstrated that nanomaterials can regulate soil properties, enhance microbial activity, and promote biodegradation processes [15]. Nevertheless, the effectiveness of these approaches remains constrained by soil conditions.

5. Challenges and limitations

Although nanomaterials have demonstrated considerable potential in environmental remediation, several challenges must be addressed before they can be widely applied. In particular, further

improvements are required in terms of material stability, environmental safety, and large-scale implementation.

5.1. Stability issues

Due to their small particle sizes and high surface energies, nanomaterials tend to aggregate and oxidize, which may reduce the number of active sites and consequently diminish their performance. Moreover, the properties of nanomaterials obtained under ideal laboratory conditions are often difficult to maintain in complex real-world environments. Factors such as ionic strength in water and soil composition can strongly affect material stability. These discrepancies between laboratory and field conditions constitute one of the major obstacles to the practical application of nanomaterials [16].

5.2. Ecological risks

Ecologically, studies have shown that nanoparticles may persist in water and soil environments for extended periods. Furthermore, they can accumulate in food chains and potentially exert adverse effects on ecosystems [17]. At present, the understanding of the ecological risks of nanomaterials remains incomplete, and assessment methods for these risks remain underdeveloped. Therefore, substantial efforts are still required to address these challenges.

5.3. Challenges in engineering applications

Significant barriers remain to translating nanomaterials from laboratory research to practical applications. Most existing studies are small-scale, whereas large-scale production often struggles with consistent material quality. In addition, the complexity and high costs associated with nanomaterial synthesis and application pose considerable challenges [18]. Large-scale implementation also requires efficient recovery and reuse strategies, which further complicates the engineering process.

Therefore, future applications of nanomaterials should focus on improving stability, environmental safety, and engineering feasibility, especially by facilitating the transition from laboratory research to real-world applications.

6. Conclusion

This study systematically reviewed the practical applications of nanomaterials in environmental remediation and analyzed their mechanisms and application strategies in the treatment of water, air, and soil pollution.

From a theoretical perspective, this review summarized the characteristics and mechanisms of various nanomaterials, thereby elucidating the relationships among material properties, pollutant types, and remediation approaches. This work supplements existing studies that have largely overlooked application-oriented classifications and pollutant-specific remediation strategies.

By integrating recent research advances, this study further compared the roles of nanomaterials across different environmental media and illustrated their mechanisms in pollutant removal processes.

Nanomaterials continue to exhibit considerable potential for practical applications and remain highly valuable for innovation in environmental remediation. However, due to insufficient experimental data and the differences in research objectives, evaluation criteria, and experimental

conditions, directly comparing research outcomes remains challenging. Furthermore, this review did not provide an in-depth discussion of the sources and impacts of nanomaterial toxicity.

Future research should focus more on nanomaterial application under complex environmental conditions, particularly with respect to improving their stability and environmental compatibility. In addition, more comprehensive environmental assessment frameworks should be established to investigate approaches for achieving ecological protection and compatibility in nanomaterial applications.

In summary, nanomaterials possess significant potential for environmental remediation; however, numerous scientific and technical challenges remain. Continued research in this field will further advance the development of nanotechnology and promote its sustainable application in environmental protection.

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