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Analysis on Application Prospect and Challenge of Nanomaterials in Environmental Protection

Minqian Zhou

Affiliated High School to Hangzhou Normal University, Hangzhou, China
2976264839@qq.com

ABSTRACT

This study aims to comprehensively analyze the application prospects and challenges of nanomaterials in environmental protection, providing theoretical support and practical guidance for the development of eco-friendly technologies. Through systematic review of domestic and international literature, this research systematically examines existing research achievements in environmental applications of nanomaterials while analyzing their unique properties. The findings indicate that nanomaterials have achieved notable successes in water, air, and soil pollution control, demonstrating broad application potential such as innovative pollutant monitoring technologies and multifunctional eco-materials. However, implementation faces multiple challenges including cost control in production processes, technical barriers in large-scale manufacturing, ecological toxicity and biodiversity impacts, as well as regulatory gaps and incomplete policies. To address these issues, the study proposes strategies encompassing low-cost production technology development, overcoming mass production challenges, establishing environmental risk assessment systems, enhancing ecological monitoring and research, promoting policy formulation, and improving regulatory frameworks which all aimed at advancing sustainable application of nanomaterials in environmental protection.

KEYWORDS

Nanomaterials; Environmental protection; Application prospect; Challenge; Countermeasures

1. INTRODUCTION

1.1. Research Background

The environmental impacts of technological development have historically exhibited a complex duality, combining positive contributions with profound negative consequences. Particularly during the global wave of industrialization, the environmental costs became especially severe. Large-scale industrial production released massive pollutants, leading to air pollution, water contamination, soil degradation, and other critical issues. These damages were profound and enduring, causing irreversible impacts on human habitats at the time. This rapid environmental deterioration not only directly threatened public health and well-being but also long-term constrained sustainable resource utilization, indirectly hindering humanity's overall progress and development. However, with continuous advancements in science and technology, humanity has gradually discovered new hope in addressing environmental challenges. Nanomaterials, due to their unique physicochemical properties, such as large specific surface area, excellent adsorption capacity, high catalytic activity, and controllable surface characteristics——, demonstrate tremendous potential in water pollution control, air purification, soil remediation, and environmental monitoring. Their applications in environmental governance are extensive. For instance: nano ZVI effectively removes heavy metal ions and organic chlorides from water; TiO_2 photocatalyzes the degradation of organic pollutants and sterilization; carbon nanotubes and graphene adsorb trace pollutants and oil residues in water. In air purification, noble metal-loaded nanocatalysts convert NOx and CO in vehicle exhaust, while nanofiber filter membranes filter PM2.5/PM10. In addition, nanosensors can monitor toxic and harmful gases, heavy metal ions and organic pollutants with high sensitivity in real time. Therefore, nanomaterials is an important research direction in the field of environmental protection.

1.2. Problem Statement

While nanomaterials demonstrate promising applications in environmental protection, current research still lacks systematic and comprehensive analysis of their potential and challenges. Existing studies predominantly focus on specific application areas or individual material types, with insufficient comprehensive evaluations of their overall environmental trends, associated risks, and regulatory strategies. Furthermore, practical engineering applications face multiple technical bottlenecks and policy barriers: the high synthesis costs and immature large-scale production processes hinder industrial adoption; ecological risks have raised widespread concerns, particularly regarding long-term impacts on ecosystem structures and biodiversity that require thorough investigation; while existing regulations lack robust environmental safety standards and full lifecycle management frameworks. Therefore, systematically mapping out development pathways and technical constraints in this field, along with proposing targeted solutions, holds significant scientific value for advancing environmental governance innovation.

1.3. Research Objectives

This study aims to analyze the application prospects and challenges of nanomaterials in the field of environmental protection, propose countermeasures, and provide support for practical applications. Specifically, it is carried out from four aspects:

(1) Review the application status of water, air and soil pollution control, analyze the technical characteristics and trends;

(2) Explore potential application directions, including new pollutant monitoring and research and development of multifunctional materials;

(3) Analyze technical, environmental and policy challenges and identify constraints;

(4) Put forward countermeasures covering technology research and development, risk assessment and policy improvement. Through this study, it is expected to provide a basis and guidance for scientific application and promote innovative development.

2. LITERATURE REVIEW

2.1. Theoretical Basis of Nanomaterials

Nanomaterials are novel materials where at least one dimension in three-dimensional space falls within the nanoscale range (typically 1-100 nm). Their unique physical and chemical properties have made them a key focus area in modern scientific research. Based on dimensional characteristics, nanomaterials can be classified into zero-dimensional nanoparticles, one-dimensional nanowires or nanotubes, and two-dimensional nanofilms [6]. These materials exhibit significant small-size effects, surface effects, and quantum size effects due to their extremely small dimensions. The small-size effect causes remarkable changes in mechanical, thermal, and optical properties of nanomaterials—such as nanoparticles showing significantly enhanced strength and hardness compared to traditional materials [8]. Surface effects arise from increased atomic density on the material's surface, leading to enhanced surface activity and adsorption capacity, which holds important application value in water pollution control and soil remediation [10]. Additionally, quantum size effects endow nanomaterials with unique electronic structures, enabling them to demonstrate excellent performance in catalytic reactions and photocatalysis processes. Macroscopic quantum tunneling effects further expand the application potential of nanomaterials, particularly playing a crucial role in microelectronic device development [10]. These theoretical foundations establish a scientific basis for the extensive applications of nanomaterials in environmental protection.

2.2. Research Progress on the Application of Nanomaterials in Environmental Protection

In recent years, significant progress has been made in the application research of nanomaterials in environmental protection, particularly demonstrating outstanding performance in water pollution control, air pollution management, and soil remediation. In water treatment applications, nanomaterials are extensively utilized for pollutant adsorption and degradation. For instance, nano titanium dioxide (TiO_2) exhibits exceptional UV light absorption capabilities and photocatalytic degradation properties, enabling efficient removal of organic pollutants from water bodies [2]. Meanwhile, nano-zero-valent iron (nZVI), leveraging its high reduction potential, is employed for heavy metal ion removal. The adsorption mechanism primarily involves both chemical reduction and physical adsorption processes [7].

In atmospheric pollution control, nanomaterials demonstrate significant potential through their ability to capture harmful gases and purify vehicle exhaust. Research indicates that nano-TiO_2 can convert sulfur dioxide (SO_2) and nitrogen oxides (NO_3) into environmentally friendly substances via photocatalytic processes [1]. Furthermore, the application of nano-rare earth catalysts in vehicle exhaust purification systems has notably enhanced catalytic efficiency while reducing toxic gas emissions.

In soil remediation, nanomaterials are primarily employed for heavy metal immobilization and organic pollutant degradation. For instance, nano-black carbon with surface oxidation modification demonstrates enhanced adsorption capacity for heavy metal ions, while nano-zero-valent iron effectively stabilizes soil-bound heavy metals through reduction processes [7, 14]. Although existing research has yielded significant progress, limitations persist across different application stages. Notably, the long-term environmental stability and ecological safety of these materials remain critical issues requiring further investigation.

2.3. Research Bottlenecks and Gaps

Although significant progress has been made in the application of nanomaterials for environmental governance, notable research gaps persist in their environmental risk assessment systems and policy regulatory mechanisms. Specifically: First, ecological safety studies remain limited, with unclear migration and transformation mechanisms of nanomaterials in environmental media and their long-term impacts on ecosystems [3]. Second, the full lifecycle management evaluation system remains underdeveloped, failing to adequately address potential risks during material production, usage, and disposal processes [14]. Additionally, existing policies and regulations contain regulatory blind spots, lacking unified environmental safety standards and standardized management frameworks [3]. This study aims to systematically analyze the current status and core challenges of nanomaterial applications in the environment, propose comprehensive countermeasures, fill these research gaps, and provide theoretical support for environmental risk management.

3. PROPERTIES OF NANOMATERIALS

3.1. Physical properties

3.1.1. Small size effect

The small-size effect of nanomaterials refers to the phenomenon where their physical properties undergo significant changes when reduced to the nanoscale. This effect is primarily manifested in alterations to mechanical, thermal, and optical properties. In terms of mechanical performance, nanomaterials typically exhibit higher strength and hardness, mainly attributed to reduced internal defect density and enhanced grain boundary strengthening effects. Taking metallic nanocrystalline materials as an example, their yield strength significantly exceeds that of traditional coarse-grained materials, providing potential advantages for their application in structural components of environmental protection equipment. Regarding thermal properties, the small-size effect alters the thermal conductivity and coefficient of thermal expansion of nanomaterials, thereby affecting their thermal stability under high-temperature conditions. Additionally, the optical properties of nanomaterials demonstrate unique characteristics due to this effect, such as blue-shifted absorption edges and quantum confinement effects. These features open up significant application potential in fields like photocatalysis and environmental monitoring.

3.1.2. Surface effects

The surface effects of nanomaterials stem from their characteristic where the proportion of surface atoms increases significantly with decreasing size. Due to the higher coordination unsaturation of surface atoms, these materials exhibit substantially enhanced surface activity. This property directly boosts their adsorption capacity and chemical reactivity. Research indicates that the specific surface area of nanomaterials correlates positively with their adsorption performance, a feature crucial for efficient removal of environmental pollutants. For instance, nano titanium dioxide and nano zero-valent iron have been widely applied in water treatment due to their high specific surface area and strong adsorption capabilities, effectively removing heavy metal ions and organic pollutants [12]. Moreover, surface effects endow nanomaterials with excellent interfacial interaction capabilities, enabling them to form stable composites with other materials. This further expands their application potential in environmental remediation.

3.2. Chemical Properties

3.2.1. Catalytic activity

Nanocatalysts demonstrate exceptional catalytic efficiency and selectivity. Their abundant and evenly distributed active sites effectively reduce activation energy, thereby accelerating reaction rates. A prime example is nano titanium dioxide, which exhibits photocatalytic degradation of organic pollutants in water under UV irradiation. Moreover, catalytic selectivity can be precisely controlled through modulation of particle size, morphology, and surface chemistry properties – a critical factor for developing high-performance eco-friendly catalysts. In automotive exhaust purification systems, rare earth nanocatalysts facilitate the conversion of carbon monoxide and nitrogen oxides, significantly reducing reliance on precious metals while lowering production costs.

3.2.2. Chemical stability

The chemical stability of nanomaterials plays a decisive role in environmental remediation applications, with its performance primarily determined by material composition, microstructure, and surface modification. Under extreme conditions such as strong acids or alkalis, these materials may experience structural degradation or functional failure. However, surface functionalization modifications or composite structure designs can effectively enhance their stability. For instance, constructing protective layers on nano-zero-valent iron surfaces can significantly inhibit oxidation processes. Current research still requires deeper exploration into the long-term stability of materials in complex environmental media, which is crucial for accurately assessing their environmental benefits and potential ecological risks.

4. APPLICATION STATUS OF NANOMATERIALS IN THE FIELD OF ENVIRONMENTAL PROTECTION

4.1. Water Pollution Control

4.1.1. Pollutant adsorption

Nanomaterials demonstrate significant advantages in heavy metal ion and organic pollutant adsorption due to their prominent surface effects and high specific surface area. For instance, nano titanium dioxide (TiO_2) exhibits excellent chemical stability and high surface activity, effectively removing heavy metal ions such as lead (Pb), cadmium (Cd), and mercury (Hg) through physical adsorption and chemical interactions. Nano-zero-valent iron (nZVI), leveraging its strong reducing properties and high reactivity, is widely used for the adsorption-reduction of heavy metal ions and dechlorination degradation of organic chlorides. It can reduce highly toxic hexavalent chromium (Cr(VI)) to less toxic trivalent chromium (Cr(III)). The primary adsorption mechanisms include electrostatic attraction, surface complexation, and pore filling, which are significantly regulated by factors such as solution pH value, ionic strength, and coexisting pollutant types. Despite their outstanding adsorption performance, practical engineering applications of nanomaterials still face key challenges including high production costs and risks associated with secondary pollution control.

4.1.2. Pollutant degradation

Nanomaterials demonstrate broad application prospects in photocatalytic and redox reaction-driven degradation of organic pollutants in water. Taking nano titanium dioxide (TiO_2) as an example, it generates hydroxyl radicals (·OH) under UV excitation, effectively decomposing pollutants such as phenol, dyes, and pesticide residues. Through modification techniques like metal ion doping, the photocatalytic efficiency of TiO_2 can be significantly enhanced, enabling efficient degradation in visible light wavelengths. Additionally, transition metal materials (e.g., nano-zero-valent iron) can effectively degrade organochlorines like trichloroethylene (TCE) and carbon tetrachloride (CCl_4) via electron transfer-mediated redox reactions. Although these materials exhibit excellent degradation performance, their long-term stability and environmental safety still require further investigation.

4.2. Air Pollution Control

4.2.1. Harmful gas capture

Nanomaterials demonstrate remarkable advantages in atmospheric capture of harmful gases, particularly in removing pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x). For instance, nano titanium dioxide can oxidize SO_2 into sulfate (SO_4^{2-}) through photocatalysis, effectively reducing its atmospheric concentration. Additionally, functionalized nanomaterials like supported metal oxides efficiently capture and decompose NO_x via chemical adsorption and catalytic mechanisms. Studies indicate that nanoscale rare earth catalysts can achieve efficient NO_x conversion even at low temperatures, providing a novel approach for industrial exhaust treatment [5]. The superior capture efficiency of these materials stems from their high specific surface area and abundant active sites, which facilitate effective interfacial interactions with harmful gases. However, practical applications of nanomaterials still face challenges regarding long-term stability and reusability.

4.2.2. Exhaust gas purification

The application of nanomaterials in automotive exhaust purification primarily focuses on catalyst development, particularly in the efficient conversion of carbon monoxide (CO) and nitrogen oxides

(NO_x). Typical applications include: Nano-scale noble metal catalysts such as platinum (Pt), palladium (Pd), and rhodium (Rh) have been widely used in three-way catalytic converters, effectively converting these harmful gases into non-toxic substances like carbon dioxide (CO_2), nitrogen (N_2), and water (H_2O). Additionally, nano-rare earth catalysts, with their low cost and high catalytic activity, are gradually becoming alternative solutions, demonstrating outstanding performance in diesel vehicle exhaust treatment. These catalysts significantly enhance the removal efficiency of harmful components through efficient redox reactions. Meanwhile, carbon-based nanomaterials and other nanocomposites are employed to improve the conductivity and thermal stability of catalysts, thereby optimizing their overall catalytic performance [12]. Despite significant progress in exhaust purification using nanomaterials, large-scale production processes and environmental adaptability remain critical challenges that need urgent breakthroughs at this stage.

4.3. Soil Pollution Control

4.3.1. Heavy metal remediation

The remediation of heavy metal-contaminated soils using nanomaterials primarily relies on dual mechanisms of reduction and adsorption. Nano-zero-valent iron (nZVI) reduces heavy metal ions to less toxic forms, while nano-black carbon significantly enhances soil's adsorption capacity for these ions. Surface-modified nano-black carbon further improves both adsorption efficiency and selectivity [13]. While this approach can improve soil quality and provide technical support for pollution remediation, its long-term environmental stability and ecological safety require systematic evaluation.

4.3.2. Organic matter degradation

The application of nanomaterials in soil organic pollutant degradation primarily relies on their catalytic activity and adsorption capacity. For instance, nano titanium dioxide generates hydroxyl radicals (·OH) through photocatalysis, effectively degrading polycyclic aromatic hydrocarbons (PAHs) and pesticide residues. Materials like nano zero-valent iron degrade organochlorines such as trichloroethylene and carbon tetrachloride via redox reactions. These processes involve electron transfer mechanisms where nanomaterials act as electron donors or acceptors [14]. Although these materials demonstrate high-efficiency degradation capabilities, practical applications still face challenges including high costs and insufficient environmental adaptability. Furthermore, it is crucial to investigate their potential impacts on soil microbial community structure and function to ensure ecological safety.

5. APPLICATION PROSPECT OF NANOMATERIALS IN ENVIRONMENTAL PROTECTION

5.1. Technical Level

5.1.1. Monitoring technology of new pollutants

Nanomaterial-based sensing technologies have significantly enhanced detection sensitivity and efficiency. Their high specific surface area and reactive properties improve sensor responsiveness while lowering detection thresholds. For instance, nano-metal oxide sensors enable real-time monitoring of harmful gases at ppb levels. Quantum dot fluorescence probes demonstrate exceptional selectivity for detecting heavy metals and organic pollutants, with the added advantage of simultaneous multi-component analysis. When integrated with artificial intelligence (AI), these innovations are poised to develop intelligent, efficient, and automated monitoring systems that meet modern environmental monitoring demands.

5.1.2. Research and development of multi-functional environmental protection materials

Multifunctional nanocomposites integrate various eco-friendly functionalities. For instance, titanium dioxide activated carbon composites demonstrate adsorption and photocatalytic capabilities, making them suitable for wastewater treatment. Surface modifications such as incorporating magnetic particles can enhance functionalities like targeted adsorption and convenient recovery. These materials show significant potential in addressing complex pollution scenarios, improving efficiency, and reducing costs. Interdisciplinary collaboration is driving green and sustainable R&D advancements.

5.2. Social Demand Level

5.2.1. Meet the needs of environmental protection

Nanomaterials provide innovative solutions to atmospheric, water and soil pollution. Their characteristics solve environmental bottlenecks. For example, they are applied in exhaust gas purification, water purification and soil remediation to reduce pollution and ensure safety. They have great potential in environmental protection.

5.2.2. Promoting sustainable development

The high efficiency and catalytic properties of nanomaterials promote sustainable development, reduce chemical energy consumption and greenhouse gas emissions. In the fields of energy, wastewater treatment and materials, they improve efficiency, recycle resources and reduce consumption. This has strategic significance for building a resource-conserving and environment-friendly society.

6. CHALLENGES OF NANOMATERIALS IN THE FIELD OF ENVIRONMENTAL PROTECTION

6.1. Technical Challenges

6.1.1. Preparation cost control

The high production costs of nanomaterials hinder their large-scale application, primarily due to expensive raw materials (such as rare metals and high-purity chemicals) and energy-intensive processes like chemical vapor deposition (CVD) and physical vapor deposition (PVD). Additionally, by-product treatment increases costs. To address this, technological innovation is needed to reduce expenses, optimize processes, improve resource efficiency, and promote eco-friendly applications.

6.1.2. Technical difficulties in mass production

The primary challenges lie in particle size control and batch stability. Particle size heterogeneity (caused by environmental fluctuations or equipment limitations) compromises performance consistency, while poor batch stability leads to variations in physicochemical properties that diminish application effectiveness (e.g., reduced reduction efficiency of nano-zero-valent iron in soil remediation). Developing advanced particle size control technologies and standardized procedures is essential to enhance practical value.

6.2. Ecological and Environmental Risks

The release of nanomaterials into the environment may exert toxic effects on ecosystems. These materials can enter ecosystems through multiple pathways, posing risks to microorganisms, plants, and animals. For instance, nanoparticles can disrupt microbial community structures. In phytoremediation, while nano-zero-valent iron promotes plant growth, prolonged exposure may impair their physiological and genetic characteristics. The toxicity to animals—particularly aquatic organisms—could accumulate through food chains, leading to chronic effects. Additionally, nanomaterials may disrupt species survival, reproduction, and ecological balance. Their direct toxicity can reduce species populations by suppressing soil microbial communities, or alter interspecies interactions by affecting plants' nutrient absorption capacity and competitive status. Indirect impacts include altered water transparency and interference with phytoplankton photosynthesis. Comprehensive evaluation of these effects is crucial for maintaining ecological equilibrium.

6.3. Policy and Regulatory Gaps and Imperfect Regulations

There exists a regulatory gap in the environmental applications of nanomaterials. The absence of unified environmental safety standards and insufficient research on their environmental impacts and long-term effects have led to a lack of basis for risk assessment. A cross-sector regulatory coordination mechanism has not been established, with overlapping or vacant responsibilities among different departments. Establishing unified standards and interdepartmental coordination mechanisms is key to bridging these gaps. Current regulations lack comprehensive lifecycle management of nanomaterials. Existing policies focus on specific stages while neglecting holistic considerations.

7. STRATEGIES TO ADDRESS CHALLENGES

7.1. Technical Strategy

Developing green and cost-effective technologies is crucial. Utilizing renewable raw materials like waste biomass can significantly reduce production costs [7]. Optimizing manufacturing processes through energy-efficient liquid-phase techniques such as solution methods and sol-gel processes enhances economic viability. Developing solvent-free or low-toxicity solvent-based processes further improves cost-effectiveness. Overcoming technical bottlenecks in large-scale production requires precise control of particle size and batch stability. Introducing surfactants or template-assisted synthesis strategies effectively improves particle uniformity. Implementing real-time monitoring technologies like dynamic light scattering (DLS) for process parameter adjustments is key to achieving precise control. Modular production line design significantly boosts both efficiency and product consistency.

7.2. Environmental Risk Response Strategy

Establish a comprehensive scientific evaluation system covering the entire lifecycle of nanomaterials. It is essential to clarify their migration and transformation mechanisms across different environmental media, while developing standardized toxicity testing criteria and assessment methodologies. Integrating multidisciplinary research findings will provide robust evidence. Strengthen monitoring and studies on their environmental behavior and ecological impacts. Establish long-term monitoring networks to track their distribution patterns and transformation processes.

7.3. Policies, Regulations and Strategies

There is an urgent need to develop targeted policies to address regulatory gaps. Establish a unified environmental safety standard system with clearly defined emission limits for all production stages. Strengthen product labeling regulations by requiring detailed disclosure of ingredient compositions and potential risks. Implement market access systems that rigorously assess environmental safety compliance. Improve comprehensive lifecycle management frameworks. Enhance manufacturing supervision through strict pollutant emission standards. Develop technical specifications and management protocols for end-of-life product disposal. Promote international collaboration to jointly establish a globally unified regulatory framework.

8. RESEARCH SUMMARY AND OUTLOOK

This study systematically reviews the application potential, current status, challenges, and corresponding strategies of nanomaterials in the field of environmental protection. Research indicates that, due to their unique surface effects, high specific surface areas, excellent catalytic activities, and chemical stabilities, nanomaterials exhibit significant potential in aspects such as the adsorption and degradation of water pollutants, the capture of harmful atmospheric gases and tail - gas purification, the remediation of heavy metals in soil, and the degradation of organic pollutants [12]. At the technical level, the development of new pollutant monitoring technologies and multifunctional environmental protection materials provides new approaches for precise environmental governance and efficiency improvement. From the perspective of social demand, nanomaterials hold important strategic significance in meeting environmental protection needs and promoting sustainable development.

However, nanomaterials still face numerous challenges in practical applications. Technically, the high preparation costs and complex large - scale production processes (such as particle size control and batch stability) are the main constraints for large - scale promotion. In terms of ecological and environmental risks, the migration and transformation behaviors of nanomaterials in environmental media, their long - term ecological toxic effects, and their potential impacts on ecological balance still require systematic evaluation and long - term monitoring. At the policy and regulatory level, there are currently issues of a lack of regulatory frameworks and an imperfect legal system, specifically manifested as the absence of unified environmental safety standards and a management mechanism covering the entire life cycle.

In response to the above challenges, this study proposes a series of corresponding strategies. Technically, efforts should be made to develop green and low - cost preparation processes, optimize synthetic routes, and overcome technical bottlenecks in large - scale production. Regarding environmental risk response, it is urgent to construct a scientific and comprehensive life - cycle environmental risk assessment system, deepen basic research on the environmental behaviors and ecological effects of nanomaterials, and establish a long - term environmental monitoring network. In terms of policies and regulations, special policies should be formulated promptly, unified environmental safety standards and market access systems should be established, full - life - cycle supervision should be strengthened, and international cooperation should be actively promoted to build a global collaborative governance framework.

Future research should focus on the following directions: (1) Continuously deepen the research on the mechanism of action of nanomaterials in environmental interface processes to improve their targeted delivery and action efficiency in complex environmental media; (2) Strengthen interdisciplinary research on environmental risk assessment and management to establish more accurate prediction models and early warning systems; (3) Promote the collaborative innovation mechanism among industry, academia, and research to accelerate the engineering transformation and application demonstration of green preparation technologies; (4) Actively participate in and lead the formulation of international standards and rules to jointly build a scientific, rigorous, and forward - looking global nanoscale environmental technology governance system. Through multi - dimensional collaborative efforts, nanomaterials are expected to provide key technical support for efficient, precise, and sustainable environmental governance.

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