

Application of Nanomaterials in Environmental Protection

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Abstract: In recent years, the rapid development of industry and agriculture has led to increasingly serious environmental pollution problems, resulting in irreversible damage to ecosystems caused by a significant number of pollutants emitted without meeting standards or even released directly. Meanwhile, climate change and frequent appearance of extreme climate aggravate this problem. In pursuit of sustainable development and a cooperative, vibrant future, humanity is increasingly concerned about environmental protection gradually. Nanomaterials exhibit unique properties due to their small size (1-100 nm in at least one dimension), including size effects, quantum size effects, surface effects, and quantum tunneling effects. What's more, nanomaterials has advanced performances, including electrical conductivity and mechanical strength, making them applicable in various fields and highly significant. This paper reviews the preparation principles and technical defects of nanomaterials and relevant devices. It also introduces the application status of nanotechnology in fields of environmental protection such as air purification, wastewater treatment and environment quality monitoring. Finally, it summarizes the research progress of nanotechnology in environmental protection. Studies show that even though nanotechnology shows tremendous potential, it still faces challenges including technology limitations, cost-effective and environmental security. Addressing these issues will require interdisciplinary research and technological innovation.

Keywords: Nanotechnology, size, environmental protection, filtration, catalysis

1. Introduction

Environmental pollution can be classified into air pollution and water pollution. Due to the presence of toxic contaminants, the persistent problem of air pollution worldwide has harmed public health to a large extent [1]. The origins of air pollutants are various, including industrial emissions, motor vehicle exhaust, agricultural activities and building construction. Among them, fossil fuel and emission from biomass consumption are main resources, with the most important pollutants being particulate matter (PMs) and volatile organic compounds (VOCs). As for water pollution control, the core purpose is to increase the availability of fresh water. In daily life, either irrigating fields, cooling equipment or laundry and cooking need a large amount of fresh water. In order to secure sufficient fresh water, people can explore strategies for controlling polluted water and sea water desalination. Except for controlling pollution, real-time monitoring is necessary and nanotechnology plays a vital role here.

Nanomaterials are objects with sizes between 1 and 100 nanometers in at least one dimension, exhibiting unique properties related to size, shape, porosity and other aspects [2-4]. Nanotechnology has developed rapidly in recent years and has been applied in a great number of domains.

This article reviews the recent progress of nanotechnology in environmental protection, highlighting its applications in air purification, wastewater treatment, seawater desalination and environmental quality monitoring. The significance of this research lies in exploring the applications of nanotechnology in environmental protection, revealing its potential in addressing air and water pollution issues, and providing innovative solutions for sustainable development.

2. The Performance and Fabrication of Nanomaterials

By examining both the performance and the fabrication techniques, people can gain insights into specific uses of nanomaterials, paving the way for advancements in technology and sustainability.

2.1. Graphene

Essentially, graphene is a two-dimensional, one-atom-thick layer of sp^2 hybrid carbon atom. The carbon atoms connect as a honeycomb like crystal lattice through σ -bonds and π -bonds. This material serves as the foundational structure for all forms of graphite: when unpacked, graphite becomes graphene (two-dimensional); when rolled up, it forms carbon nanotubes (one-dimensional); and when folded, it transforms into fullerenes (zero-dimensional).

As for graphene, it can be classified into nanoporous, atomically thin graphene films and graphene-based laminar membranes. The function principle of graphene films is that it requests wastewater or other unfiltered liquid to cross a high-quality monolayer or few-layer 2D membrane with properly-sized nanoholes and this film plays the role of a molecular sieve that allows water and gas molecules to pass and prevents unneeded particles like dyes, salts, etc. Therefore, the membrane's permeability (high throughput of needed substance), selectivity (high blocking of unwanted substance), and stability (high chemical and mechanical stability) are important criteria of the film quality, which depends on the pore structure of graphene to a large extent. There are many approaches that have been summed up so far, such as focused ion beam irradiation, plasma etching, template-assisted etching and chemical oxidative etching. In 2010, Garaj et al. Used an electron beam and ultraviolet to induce oxidative lithography to prepare nanoporous graphene for DNA translocation [5]. Koenig and his colleagues fabricated nanoporous graphene through oxidative etching induced by ultraviolet in 2012 [6]. However, limited by various factors, these approaches cannot fabricate large-area graphene membrane. In 2018, Park's team successfully grew single-layer porous graphene on a W/Cu support; however, due to material size constraints, the resulting aperture was typically larger than 10 nm, rendering it ineffective for filtering Na^+ and salt ions. [7]. What is more, Zhou et al. reported that the burning of microwave nanoporous graphene films can be gained with metal-based nanoparticles to induce and oxidate carbon [8]. Up to now, the fabrication of graphene with a large area has technologies like Chemical Vapor Deposition (CVD) growth and mechanical exfoliation from graphite. However, the technical bottlenecks of drilling properly sized nanopores in a large-area graphene film have not been settled now. Therefore, it is essential to explore advanced technologies for fabricating high-performance, low-cost nanoporous films and to investigate diverse applications for these nanoporous membranes, which has vital meanings for promoting their properties and environmental production [9].

2.2. Nanofibers

Nowadays, the fabrications of nanofibers can be classified through three directions: first, according to the order of preparation, it can be divided into bottom-up and top-down approaches. Secondly, there

are Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD) and biological techniques based on principle. Thirdly, spinning techniques and non-spinning techniques are defined, which depend on whether they involve spinning.

What's more, bottom-up approaches consist of mechanical gridding, vapor deposition, electrospinning, centrifugal spinning, self-assembling, interface aggregation, and freeze drying [10-14]. For top-down approaches, small-sized particles are usually used to fabricate nanoparticles [15].

3. Application of Nanotechnology in Environmental Protection

3.1. Air Purification

There are four primary methods for controlling air pollutants: filtration, absorption, photocatalysis and room-temperature catalysis. Compared with traditional materials, nanomaterials have a larger special surface area and their unique electrical, magnetic and catalytic properties enable them to have more advantages in air pollutant control approaches [16]. Therefore, the introduction of nanotechnology provides fantastic solutions to deal with air pollution.

With typical sizes under 100 nm, nanomaterials exhibit small size effects, quantum size effects, surface effects, and quantum tunneling effects. This enables their application not only in particle filtration, gas absorption, bacterial disinfection, and catalysis but also in reducing particulate matter (PM) and volatile organic compounds (VOCs) such as formaldehyde (HCHO). Furthermore, nanomaterials are often more advantageous than traditional materials due to their simple equipment requirements, milder working conditions and affordability.

Specifically, for controlling particular matter (PM), filtration and absorption are commonly employed methods. Li's team proposed that efficient air filtration can be realized through triboelectric nanomaterials. However, relying solely on volatile organic composite absorption cannot solve fundamental problems; thus combining absorption with decomposition enhances control efficiency to a large extent [17]. Tang et al. pointed that photocatalytic technology offers obvious advantages in dealing with air pollution especially for volatile organic compounds [18].

3.2. Sewage Controlling

Nanomaterials show enormous potential in sewage controlling and they can remove pollutants in wastewater efficiently and reduce costs.

In agricultural production, fertilizers containing nitrogen, phosphorus, and potassium are commonly used, but substantial amounts can leach into water bodies, leading to problems such as algal blooms and red tides, which pose significant ecological threats. Therefore, getting rid of these elements before emission is necessary. Nanomaterials can reduce contamination through absorption and catalysis. For example, in 2020, Dan et al. reported an approach of wastewater treatment through ozone-based advanced oxidation processes facilitated by nano-catalysts [19]. Later, a method for extracting metal oxide nanoparticles from agricultural waste was developed, enabling the degradation or enrichment of excess elements while absorbing them. This allows for mass usage of nanotechnology in disposing of agricultural waste. Fayomi proposed a method of producing silicon dioxide nanoparticles with agricultural waste in 2022, which reduces pollution and promotes resource reuse at the same time [20].

Industrial wastewater usually contains a significant number of metal elements, including mercury (Hg), cadmium (Cd), lead (Pb), chromium (Cr), and arsenic (As). Traditional treatment methods, such as chemical precipitation, ion exchange, adsorption, membrane separation, and biological treatment, tend to be costly and require expensive equipment. The integration of nanotechnology can significantly enhance these processes. In 2019, Ali's team treated harmful contaminants in

wastewater with graphene-based adsorbents [21]. In 2023, Sharma and his team investigated new technologies for sustainable water management around nanotechnology [22].

Seawater covers 70% of the earth's surface area. As the most abundant water resource, purifying seawater can gain plenty of usable fresh water. Dan's team researched a proper water-dealing technology; it can not only remove macroscopic and microscopic contaminants but desalinate seawater. Tip-functionalized, non-polar internal carbon nanotubes (CNTs) provide strong attractions to polar water molecules and reject salts and pollutants. Nanotubes have low energy consumption and a self-cleaning function and this makes them do better than traditional membranes [23].

3.3. Environmental Monitoring

In addition to pollutant control, nanotechnology has brought a lot of revolutions for environmental monitoring as well. With high-sensitivity nanosensors, it is now possible to rapidly detect micro-contaminants, especially in atmosphere, water and soil, which greatly improve monitoring efficiency and accuracy.

For example, in 2014, Gao et al. researched the application of nanotechnology in monitoring polluted soil and underground water, showing its efficient testing ability in complicated environment [24]. Furthermore, Jian et al. developed a functional PEDOT-ZnO nano heterojunction gas sensors and monitoring system based on accurate dielectrophoresis (ADEP) technology. In addition to high sensitivity and low cost, this sensor shows enormous potential of sustainable environmental monitoring [25].

These research advancements highlight the bright future of nanotechnology in environmental monitoring, paving the way for more efficient and accurate systems for supervising environmental quality.

4. Challenges and Future Prospects

Nanomaterials shows tremendous potential in environmental protection through their typical strategies, such as small-size and high special surface area, but they still face several challenges.

First, the physical application of nanomaterials is hindered by high fabrication costs, complicate production processes and a strong dependence on precise equipment, leading to the limitation of large-scale production. For example, the fabrication of nanomaterials usually need high-precision experimental equipment and strict operating conditions, which increase the costs and limit the wide application in environmental efforts.

Secondly, integrating nanotechnology into existing eco-friendly systems pose difficulties. For instance, although nanomaterials can effectively clear pollutants, combining with traditional materials and systems for improvement is complex. Furthermore, the potential environmental risks of nanomaterials have caused widespread attention for they may be released and become new pollution sources.

What's more, nanotechnology faces challenges in environmental monitoring. While nanosensors are known for their high sensitivity and rapid response, their stability and reliability need enhancement. For example, nanosensors often lack long-term stability in complicated external environments and may calculate inaccurate data. Meanwhile, costs and technology hinder the commercialization and large-scale application of nanosensors.

In spite of limitations above, the future of nanotechnology in environmental protection remain promising. In sewage treatment, nanomaterials can remove heavy metal ions, organic contaminants and etc., which help purify water quality. In the field of air pollution control, nano-catalysis enhances decomposition efficiency of harmful gases obviously, thereby improving air quality. In environmental monitoring, nanomaterials can dramatically improve monitoring accuracy.

As research continues to advance, nanomaterials are expected to breakthrough technical bottlenecks, enabling large-scale, low-cost applications. This progress could revolutionize global environmental protection efforts and establish nanotechnology as a key solution for addressing environmental challenges.

5. Conclusion

This paper explores the research progress of nanotechnology in environmental protection, highlighting its potential and effects in air purification, wastewater controlling, seawater desalination and environmental quality monitoring. Through analyzing the strategies of nanomaterials, this paper finds that their small size and high specific surface area significantly enhance contaminant removal efficiency, thus improving the quality of air and water and promoting environmental governance technology. For instance, in air purification, nanomaterials improve the handling of particulate matter and volatile organic compounds. In wastewater treatment, nano-catalysts enable efficient removal of pollutants from industrial and agricultural wastewater. In environment monitoring, the high sensitivity of nano-sensors makes it possible to examine rapidly.

However, there are still some shortcomings in this article. First of all, financial analysis of nanotechnology is relatively limited, leading to a lack of the comprehensive evaluation of mass production and economic benefits of nanomaterials. Furthermore, even though it has concluded many research progress, discussions on long-time stability and safety of nanomaterials in practical application are relatively vacant. Looking ahead, the development of nanomaterials in environmental protection should focus on aspects below. First, promoting mass, low-cost production of nanomaterials can be more widely used in environmental protection. Second, enhancing research into the ecological safety of nanomaterials is essential to ensure they do not pose potential risks to the environment and human health. Thirdly, promoting the combination of nanotechnology with existing environmental protection technologies will help develop composite eco-friendly materials and equipment, thus improving the overall efficiency of environmental governance. Lastly, strengthening interdisciplinary research that combines knowledge from physics, chemistry, environment science, and other fields will push forward the innovation and application of nanotechnology. With the continuous development of science and technology, nanotechnology is expected to become an indispensable tool to settle global environmental problems and contribute to sustainable development.

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