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Common methodologies for treating environmental issues with nanomaterials

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Abstract. With rapid industrialisation and population growth, the Earth's ecological environment now confronts increasingly complex and diverse challenges. Traditional pollution treatment methods, such as activated sludge for sewage and electrostatic precipitation for air pollution, can effectively manage most environmental pollution. However, some pollutants (e.g. metals, organic dyes, gaseous trace pollutants in heavy water) either cannot be addressed by conventional methods or are prohibitively expensive. Hence, there is a pressing need to develop new environmental technologies. The emergence and development of nanotechnology and nanoscience present novel opportunities for environmental governance, as nanomaterials offer advantageous traits such as high specific surface area, catalytic activity, and photocatalytic activity. This renders nanomaterials better adsorbents, catalysts, and sensors compared to traditional materials. This article examines three methods - adsorption, filtration, and degradation - through which nanomaterials can be utilised to address environmental challenges, and the advantages and disadvantages of such methods are discussed. Finally, this article provides insights in response to the findings presented.

Keywords: Nanomaterials, Adsorption, Filtration, Degradation

1. Introduction

Global pollution is a complex issue that is interlinked with numerous industrial, social, and economic factors. The era of speedy scientific and technological progress, from the start of the Industrial Revolution, enabled large-scale mechanised production and urbanisation. The substantial burning of oil, coal, and natural gas has led to significant air and water pollution, comprising the release of massive amounts of greenhouse gases. These gases - for example, carbon dioxide, methane, and nitrogen oxides - directly contribute to global warming. The process of combustion creates air pollutants, which include sulphur dioxide, carbon monoxide, and suspended particulate matter [1], all of which pose a risk to human health. Industrial activities have introduced a range of harmful chemicals and heavy metals into the environment, including mercury, lead, and cadmium, which continue to persist and potentially have long-term effects on ecosystems and human health. Plastic waste in aquatic environments is increasing in significance as an environmental challenge now. The existence of macro- and microplastic particles in the oceans poses a serious challenge to the natural decomposition process, consequently posing a significant threat to marine ecosystems. United Nations Environment Programme (UNEP) states that the largest direct risk to the environment's health is airborne pollutants, with 99% of the world's populace inhaling harmful air. Exposure to air pollution markedly elevates the risk of contracting illnesses like stroke, heart disease, and lung disease, as well as cancer. More than 6.7 million premature deaths worldwide, each year, are attributed to this phenomenon. Similarly, wastewater poses a mounting danger to both health and the environment, with greenhouse gas discharges reaching almost equivalent levels to those of the aviation industry.

Nanomaterials are gaining increasing attention for potential use in environmental governance due to their unique advantages over conventional materials. One major advantage is their high surface area to volume ratio, which enhances their reactivity and adsorption capacity. This property makes them effective for removing pollutants from water and air. Additionally, these materials exhibit an improved catalytic performance, promoting the acceleration of chemical reactions, particularly the degradation of organic pollutants. Nanomaterials possess targeted functionality, enabling scientists to modify them physically or chemically to specifically tackle certain pollutants. Moreover, these materials exhibit high mechanical strength and may be applied in numerous forms to treatment systems, including suspensions, coatings, or membranes, thus expanding treatment options significantly. Notably, nanomaterials are adept at removing trace contaminants with great efficacy. On this basis, this paper will study the role of nanomaterials in environmental remediation according to various mechanisms including adsorption, filtration, and degradation/decomposition.

2. Adsorption

Certain nanomaterials possess a porous configuration. For instance, activated carbon nanoparticles and metal-organic framework (MOF) nanoparticles are renowned for their porosity [2]. These pore structures offer a large surface area. Certain MOFs (such as MOF-210 and NU-100) are notable for their exceptional porosity [3]. They both possess a specific exceeding 10,000 m^2/g. Additionally, both exhibit a highly porous three-dimensional network structure with a variety of pore sizes. This structure allows for designing materials with different pore sizes to selectively adsorb specifically sized molecules while rejecting others. This structure exhibits diverse pore sizes, enabling the formulation of varying pore sizes. This characteristic selectively absorbs target molecules and discriminates against others. Its potential as a screening and sorting agent makes this nanomaterial highly applicable in wastewater treatment and gas purification. Additionally, porous materials with varied pore sizes offer a larger usable space. This provides valuable opportunities for developing more porous materials. Materials with varying pore sizes can offer more space within their porous structure, resulting in an increased total adsorption capacity. Regarding adsorption kinetics, micropores enable faster adsorption as molecules tend to diffuse more swiftly in the micropores. While mesopores and macropores offer superior transport channels, facilitating swift entry and exit of molecules from the material, the various pore sizes of nanomaterials can be effectively harnessed for adsorption kinetics, thereby augmenting the efficiency of adsorption.

At the nanoscale, it is important to consider the role of van der Waals forces owing to factors such as high specific surface area, short interaction distances, and high atomic densities. These forces have a broad range of effects that can significantly influence the adsorption of materials. Since nanomaterials typically possess a high specific surface area, this enables a vast number of surface atoms to interact with adsorbate molecules via van der Waals forces. As soon as the initial layer of molecules attaches to the surface of the nanomaterial through van der Waals forces, additional molecules have the ability to adhere to these already adsorbed molecules, thereby creating a multimolecular layer that further enhances the efficiency of adsorption with the nanomaterial. Most atoms of nanomaterials are situated on the surface or boundary of the material, where the boundary atoms possess unpaired electrons. These electrons have the ability to create weak chemical bonds or physical interactions with other substances, promoting adsorption. Furthermore, some boundary atoms may undergo charge redistribution altering their charge state, thereby promoting certain charge-driven adsorption phenomena. For example, when exposed to light, TiO_2 nanoparticles generate electron-hole pairs [4]. The creation of these holes can develop a positive surface charge, subsequently promoting the absorption of negatively charged organic pollutants.

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Currently, numerous nanomaterials are utilised in the field of environmental protection. For instance, in safeguarding the atmosphere, hazardous gases like sulfur dioxide, carbon monoxide, and nitrogen oxides can impair human health. Traditional methods, such as applying activated carbon or synthetic resin adsorbent materials, can minimise certain pollutants. However, in terms of conventional air purification, their efficiency is significantly limited. In the case of sulphur compounds and certain heavy metal vapours such as mercury vapour, adsorption efficiency is limited, and synthetic resins may have lower adsorption efficiency for non-target pollutants. However, nanomaterials, including porous carbon nanomaterials, MOF-based nanomaterials, and metal oxide nanomaterials, can adsorb harmful gases in the air, such as certain metal vapours. Additionally, these nanomaterials can remove air pollutant gases through photocatalytically facilitating some chemical reactions. This property can be utilised in the removal of air pollutants through a photocatalytic reaction, converting formaldehyde into harmless CO_2 and H_2O.

3. Filtration using nanomaterial membranes

Nanomembranes, particularly carbon nanotubes (CNTs) and graphene [5], have the capability of selectively retaining a broad spectrum of pollutants to attain strict water quality standards. Given the mounting resource constraints and water pollution issues, nanomembranes offer an energy-efficient, effective, and sustainable approach to water treatment.

Carbon nanomembranes have demonstrated outstanding effectiveness in water treatment, owing to their distinctive pore structure [6], high specific surface area, and surface charge characteristics. The membrane's nanoscale pores operate like molecular sieves, enabling unrestricted passage of water molecules while effectively eliminating impurities. Moreover, the high specific surface area endows the membrane with a more substantial physical adsorption capacity, enabling efficient removal of both organic and inorganic contaminants. The surface charge properties of carbon nanomembranes facilitate their electrostatic uptake of charged contaminants present in water. Additionally, they can be chemically manipulated to boost their efficacy in selectively targeting particular pollutants by increasing their adsorption affinity. Moreover, the surface can undergo chemical alterations to integrate specific functional groups such as carboxyl, amino, or thiol groups [7]. These functional groups within the membrane can instil specific charges or chemical properties that augment the interaction of the membrane with distinct contaminants in the water. For instance, the inclusion of carboxyl groups can result in the formation of ligand bonds with positively charged metal ions in water, like lead and cadmium, resulting in improved adsorption efficiency. Furthermore, other functional groups can enable interactions with certain contaminants leading to an augmented capacity and selectivity of the membrane, contingent on their individual chemical characteristics. By incorporating functional groups, this technique enhances the adsorption affinity of nanomembranes for pollutants, resulting in efficient and specific water treatment. Meanwhile, carbon nanomembranes, specifically CNTs and graphene [5], possess a nanoscale channel structure that facilitates the swift and near-unrestricted flow of water molecules, while prohibiting larger contaminant molecules or ions. This rapid water transport phenomenon decreases the water flux resistance of the membrane, leading to lower energy demands for filtration and displaying noteworthy water molecule transportation levels in water treatment applications. Furthermore, the chemical configuration of carbon nanomembranes provides them with remarkable stability under chemical circumstances. They maintain their performance and integrity in acidic, alkaline, or salt solution environments, making them highly durable and reliable for various water treatment applications.

4. Degradation/decomposition

Nanomaterials offer more contact and reaction sites for pollutants due to their high specific surface area, increasing the efficiency of degradation. Furthermore, specific nanomaterials, including TiO_2 [8], possess photocatalytic properties, which enable them to activate and decompose organic pollutants under light irradiation because of their quantum effects and surface activity. This method of degradation driven by light provides a green, energy-efficient pathway for environmental remediation.

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Nanomaterials can be modified to achieve the selective degradation of specific pollutants. When compared to traditional physical adsorption methods or simple separation techniques, nanomaterials can accomplish complete mineralisation and transformation of pollutants, eliminating the possibility of secondary pollution.

Nanomaterials are recognized and widely studied for their unique properties and versatility in degrading pollutants. For instance, when exposed to UV light, TiO_2 nanoparticles can generate reactive radicals that absorb light energy and excite electron and hole pairs, thus showcasing their effectiveness in this area. Excited electrons interact with adsorbed oxygen or water molecules on the surface of TiO_2, forming superoxide anions or hydroxyl radicals. These radicals are highly oxidising, able to attack and degrade organic pollutants, mineralising them to produce carbon dioxide and water. This process is effective in removing substances like dyes and pesticides. Zero-valent iron nanoparticles generate a reduction in pollutants by transferring electrons from the iron particles when they come in contact with specific pollutants, such as chlorinated organics. For instance, trichloroethylene is changed into ethylene or methane and hence made relatively harmless in the presence of zero-valent iron [9]. This zero-valent iron nanoparticle-based reduction technology offers an efficient and direct treatment for certain pollutants that are resistant to biodegradation while evading the production of detrimental byproducts. Given its vast surface area and potent chemical activity, the graphene series can adsorb and catalyse the degradation of a broad spectrum of pollutants. In addition, gold and silver nanoparticles have displayed exceptional performance in the field of environmental catalysis. These nanoparticles are able to efficiently degrade specific organic pollutants, such as dyes, thanks to their ability to enhance the localized electromagnetic field and facilitate electron transfer. Silver nanoparticles are acknowledged for their antimicrobial properties, which efficiently hinder the growth of various bacteria and viruses as they interfere with the metabolism and DNA replication of microorganisms. Gold and silver nanoparticles combined present efficient environmental management solutions [10], featuring the degradation of organic pollutants and antimicrobial activity. The main advantage of magnetic nanomaterials, like iron oxide nanoparticles, lies in their magnetic properties. Once bonded, these nanoparticles may be isolated from water by applying an external magnetic field [11]. This simplifies the process of contaminant treatment and facilitates the recovery and reuse of nanomaterials, thus achieving effective and environmentally friendly water treatment and resource conservation. Overall, these nanomaterials offer a productive and comprehensive approach to environmental remediation, enabling the efficient elimination of pollutants and the reuse of resources.

5. Conclusion

The use of nanomaterials in environmental remediation is becoming increasingly popular, particularly in the areas of adsorption, membrane filtration, and degradation. nanomaterials possess excellent adsorption capability due to their high specific surface area and adjustable surface functional groups, enabling the effective clearance of a wide range of pollutants. Nanomembranes, including nanocomposite and nanoporous ceramic membranes, enable precise separation of molecules and provide efficient contaminant retention. Additionally, some photosensitive nanomaterials can generate free radicals when activated by light, contributing to pollutant degradation. However, these nanotechnologies present certain challenges. The regeneration and recycling of nanosorbent materials pose key issues; prolonged usage may lead to saturation and diminished activity. Nanomembranes may undergo clogging or performance degradation as a result of prolonged filtration. The stability of nanomaterials and their potential ecological threats are currently the focus of numerous researchers. In future developments of nanomaterial applications, emphasis should be given to their efficacy, stability, renewability and ecological safety. Furthermore, detailed research into the life cycle assessment and potential ecological hazards posed by nanomaterials is imperative to guarantee that nanotechnology genuinely delivers environmentally sustainable advantages for remediation.

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