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Application of Adsorption Nanomaterials in Water Treatment

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Abstract. Water pollution has now become one of the biggest environmental problems in the world. It seriously destroys the balance of the water ecosystem and threatens human health through the food chain. Industrial wastewater often contains harmful pollutants such as heavy metals, organic dyes, and drugs, and so on, but these are difficult to remove by conventional treatment methods. There are some problems with the old methods like sedimentation, coagulation, membrane filtration, and so on. They work slowly, cost a lot, and cannot remove low amounts of pollutants in water well, and they have many other problems. In recent years, nanomaterials used for adsorption pollutants have shown great potential, and this discovery has led scientists to begin studying this new material. They have a large surface area, adjustable surface, large pore volume, and strong adsorption capacity. This article discusses adsorption mechanisms, types of nanomaterials, current applications, and challenges in water treatment, as well as future ideas for smart nanomaterials and green manufacturing methods.

Keywords: Adsorption, nanomaterials, water Treatment

1. Introduction

Water pollution has become one of the important environmental issues that the world needs to face. The wastewater released from industrial work often contains harmful pollutants such as heavy metals, organic dyes, drugs, and chemicals, and so on. These pollutants not only damage aquatic ecosystems, but also finally endanger human health through the ecological food chain. Before the widespread use of nanomaterials, people used traditional water treatment methods such as precipitation, coagulation, membrane filtration, etc. However, there are still problems such as low efficiency, high operating costs, insufficient ability to remove low concentration pollutants in water, and poor pollutant removal efficiency in removing pollutants. For example, precipitation method has low removal efficiency for low concentration heavy metals in water, while coagulation method may produce a large amount of sludge, which can easily have counterproductive effects. Meanwhile, membrane filtration technology also faces issues such as membrane fouling (a type of water pollutant, such as colloidal bacteria, that can adsorb onto the membrane surface or pores, reducing membrane water production) and high costs. These issues indicate that people urgently need a new, lower cost, and more environmentally friendly water treatment method. In recent years, scientists have discovered nanomaterials and found that they are very effective in treating water. Therefore, scientists have begun to try to use nanomaterials to improve water treatment technology. Due to their

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large surface area, diverse surface chemical properties, and micropores, nanomaterials precisely compensate for the shortcomings of traditional technologies. And because of these characteristics, they can better adsorb and remove pollutants. Furthermore, their size and active surface help to remove numerous contaminants more quickly and effectively than using outdated techniques [1]. As a result, nanoparticles are a fantastic option for treating water and a product deserving of sustainable development.

2. Adsorption mechanisms

Pollutants are generally treated through physical and chemical adsorption, as well as specific interaction pathways, which are the fundamental methods for nanomaterials to demonstrate their excellent adsorption capabilities. These mechanisms not only provide different adsorbents with higher efficiency for different pollutants, but also provide theoretical basis for material optimization methods. This can provide a deeper understanding of these processes, which can help create more effective pollution removal technologies.

2.1. Physical vs. chemical adsorption

Physical adsorption and chemical adsorption are the two most important methods for removing pollutants from nanomaterials. Among them, physical adsorption, also known as van der Waals adsorption, is due to weak forces between molecules for adsorption. It is usually reversible, uses low heat, and can form many layers. It works fast and has wide use, but it is not very selective.

Chemical adsorption makes chemical bonds between the pollutant and the surface of nanomaterials. This happens by electron transfer or sharing. The forces are much stronger, 200–500 times stronger than physical adsorption. Chemical adsorption is more selective and stable. It works well for metals and complex organic molecules.

2.2. Pollutant-specific interaction pathways

Different pollutants interact with nanomaterials in specific ways to achieve removal. Heavy metal ions such as Pb^{2+} and Cd^{2+} are often captured through surface complexation. During this process, functional groups such as amino groups will directly bind with metal ions. In addition, different pollutants exhibit different behaviors during the process, just like organic pollutants, colors and drugs are usually adsorbed through hydrogen bonding or π - π stacking. Researchers have studied these interactions using complex instruments and validated this mechanism through Fourier transform infrared spectroscopy and X-ray absorption spectroscopy, providing useful directions for creating more practical and effective nanomaterials for these technologies.

3. Nanomaterials for water treatment

Metal oxide nanoparticles, carbon based materials, and composite materials are the three major types of nanomaterials used in adsorption. In water treatment, each type of nanomaterial has its unique properties. Carbon based materials are lightweight and easy to modify, metal oxides are stable, and composite materials combine the advantages of these two materials. If the factory still finds their efficiency unsatisfactory, they can achieve the requirements through surface functionalization, element doping, or mixed structures. Finally, recognizing their differences provides a solid foundation for evaluating their practical application potential in wastewater treatment.

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3.1. Carbon-based materials offer tunable adsorption properties

Due to the large surface area and abundant active groups of carbon nanomaterials, carbon nanomaterials such as graphene oxide (GO), carbon nanotubes (CNT), and activated carbon exhibit excellent adsorption properties and have been favored. Their structural flexibility and ability to add various functional groups provide them with unique advantages, enabling researchers to more effectively customize their exclusive adsorbents for specific pollutants. For example, graphene oxide contains oxygen rich functional groups, including hydroxyl, carboxyl, and epoxy resins, which help detect and remove organic pollutants and heavy metals. According to research reports, functionalizing lead with amine, thiol, or sulfonic acid groups can significantly improve its performance and increase its adsorption capacity, with adsorption capacity reaching 800-1200mg/g. Meanwhile, carbon nanotubes provide a very high surface area to volume ratio. Similar to how nitrogen or sulfur doping further accelerates adsorption and improves performance, adding additional functional groups can promote metal absorption when treated with acid or oxidation techniques. On the other hand, the surface area and pore volume of activated carbon can be increased through nanoscale engineering. When paired with metal nanoparticles, its adsorption efficiency for organic pollutants will also be improved. Overall, the main advantage of carbon based materials is their multifunctionality, as they can be chemically modified, doped, or mixed with other nanomaterials to improve their efficiency and recyclability in water treatment systems.

3.2. Metal oxide nanoparticles provide stability and selectivity

Compared with carbon based materials, metal oxides have a more stable structure and stronger affinity for pollutants, making them particularly effective in treating pollutants in harsh water treatment environments. Due to their unique catalytic properties, they convert pollutants while adsorbing them. For example, iron oxide nanoparticles are particularly attractive because they can be easily collected with magnets, thereby reducing processing costs and preventing secondary pollution. In addition, functionalized iron oxide has a high affinity for toxic heavy metals such as arsenic and chromium, making it suitable for groundwater remediation [2]. Titanium dioxide nanotubes have a dual function of adsorbing pollutants and decomposing persistent organic molecules under illumination. This photocatalytic activity enables them to complete removal and degradation in one step, thereby improving the efficiency of treating drug residues or dyes [3]. In areas where groundwater is contaminated, alumina nanosheets can accurately provide safe drinking water due to their extraordinary effectiveness in removing fluoride and arsenic from water [4]. Overall, metal oxide nanoparticles stand out due to their durability, selectivity, and versatility. Their ability to combine adsorption and catalytic processes highlights their importance in sustainable and large-scale purification applications.

3.3. Composite materials combine multiple advantages for enhanced removal

Composite nanomaterials combine the advantages of the two materials mentioned above. They have higher adsorption, better selectivity, and some additional functions. GO-MOF composite materials are a good example. They combine the surface of GO with the porous structure of MOF, allowing them to adsorb volatile organic compounds such as benzene and ethanol up to 72-77cm ^{3}/g. The best performance occurs with 3–5 wt% GO [5]. Another case is magnetic chitosan beads. Chitosan is a natural polymer. It contains amino and hydroxyl groups. When combined with magnetic particles, the beads adsorb metals, dyes, and pharmaceuticals. They are biodegradable and can be collected

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with magnets. This makes them efficient and environmentally friendly [6]. A third example is molecularly imprinted nanomaterials (MINs). These are made by forming polymers around a target molecule. Once the target is removed, specific cavities remain. These cavities can selectively capture the same or similar molecules. MINs are highly selective, stable, and reusable. They work for metals, dyes, and pharmaceuticals [7, 8]. Recent studies confirm their potential. In 2023, a MIN removed tetracycline antibiotics with over 90% efficiency. In 2024, MIN-coated magnetic nanoparticles were reported for arsenic removal. Photo-responsive MINs have also been developed. These systems release pollutants under light and regenerate automatically. Such innovations show that composites, especially MINs, can meet complex water treatment needs with precision and efficiency.

4. Current applications

The practical applications of nanomaterials in water treatment are already evident, with implementation in both household-level drinking water purification and large-scale industrial wastewater management. Their high adsorption efficiency, selectivity, and potential for regeneration provide advantages over conventional treatment technologies. However, their widespread adoption is influenced by economic feasibility, scalability, and long-term stability.

4.1. Drinking water treatment

Nanomaterials play an important role in drinking water purification. In Bangladesh, iron and TiO_2 nanofilters have been used to provide arsenic-free water. The cost is about $1 per cubic meter, which makes the solution affordable [9]. In developed countries, silver nanoparticle filters are common in homes. They can remove drugs and hormone disruptors. Current estimates suggest that 15–20% of households in high-income nations already use these filters [10]. These examples prove the practical value of nanomaterials in safe drinking water supply.

4.2. Industrial wastewater treatment

Industrial wastewater usually contains both metals and organic compounds. Nanomaterials show strong performance in both cases. In electroplating wastewater, magnetic carbon nanotube composites can adsorb 300–400 mg/g of copper and nickel ions. They also regenerate in less than five minutes [11]. This rapid cycle supports efficient reuse. In textile wastewater, graphene oxide aerogels can remove dyes at concentrations up to 1200 mg/g. Compared with traditional treatment, costs are reduced by around 40% [12]. These reductions offer major benefits to industry. However, scaling up remains difficult. Continuous flow systems often lose efficiency. Problems such as fouling, scaling, and incomplete regeneration still limit industrial adoption. Solving these issues is crucial for broader application.

5. Future perspectives

The future progress of water treatment based on nanomaterials will depend on technological innovation and sustainable production methods. The next generation of nanomaterials is expected to provide multifunctional properties for more efficient work, improve recyclability to reduce waste, and minimize environmental impact, thereby supporting wider implementation in global water purification systems.

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5.1. Material innovations

Future nanomaterials will be smarter and more adaptable. Many will respond to pH, temperature, light, or magnets. These properties allow pollutants to be captured and released with ease. Biomimetic coatings, such as polydopamine, can improve stability in water. Single-atom adsorbents are another frontier. They expose maximum active sites and offer very high selectivity [13,14]. These advances will expand the scope of applications and improve efficiency.

5.2. Sustainable manufacturing

Sustainable production is equally important. Conventional synthesis uses high energy and toxic chemicals. Green synthesis can reduce energy use by 60–80%. Plants, algae, or microorganisms can replace harmful reagents. Agricultural or electronic waste can also serve as feedstock. This supports recycling and reduces waste. New methods such as 3D printing improve control over structure while keeping nanoscale features. These methods also cut costs [15,16]. Together, such approaches make nanomaterials safer, cheaper, and more sustainable.

6. Conclusion

Nanomaterial-based adsorbents have changed researchers' views on water purification. They combine high efficiency, strong selectivity, and wide versatility. Carbon-based materials, metal oxides, and composite materials all have their unique advantages. Carbon materials have flexibility and are easy to modify. Metal oxides provide stability and catalytic function. Composite materials have multiple advantages. Each type can effectively remove heavy metals, dyes, drugs, and other pollutants, helping factories reduce costs.

The application is already visible in the real system. Nanomaterials can provide safe drinking water for people after treating pollutants in water and reduce the cost of industrial wastewater treatment. Although they have performed excellently, challenges still exist, and there are many issues that need to be addressed, such as scaling and reduced efficiency in continuous flow systems. Regeneration is not always complete. Cost may also become a barrier to large-scale adoption.

The future looks very promising. Intelligent adsorbents will respond to environmental signals. Single-atom materials will provide record-breaking selectivity. Biomimetic coatings will extend the lifespan of materials. Meanwhile, green synthesis and waste-based raw materials will make production safer and cheaper. 3D printing will enable precise design and large-scale production.

Overall, these advances indicate a significant shift. Nanomaterials may shift from experimental systems to mainstream technologies in global water treatment. If the challenges in scale and regeneration are addressed, they can provide safe, affordable, and environmentally sustainable solutions on a global scale. This transformation can play a central role in addressing the global water crisis and ensuring that future generations have access to clean water.

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