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Review

Designer carbon nanotubes for contaminant removal in water and wastewater: A critical review

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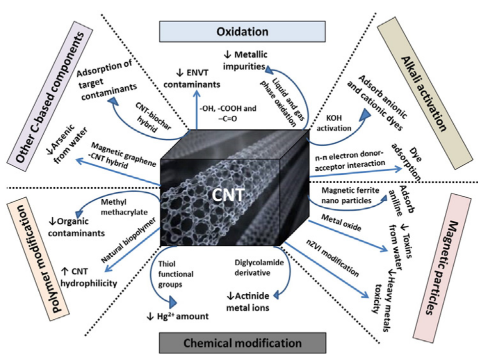
HIGHLIGHTS

- CNTs can be designed through specific functionalization or modification process.
- Designer CNTs can enhance contaminant removal efficiency.
- CNTs can facilitate recovery and regeneration of nanomaterials.
- CNTs hold potential applications in wastewater purification and desalination.
- Further research is needed to enhance commercial acceptance of CNTs.

GRAPHICAL ABSTRACT



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ABSTRACT

The search for effective materials for environmental cleanup is a scientific and technological issue of paramount importance. Among various materials, carbon nanotubes (CNTs) possess unique physicochemical, electrical, and mechanical properties that make them suitable for potential applications as environmental adsorbents, sensors, membranes, and catalysts. Depending on the intended application and the chemical nature of the target contaminants, CNTs can be designed through specific functionalization or modification processes. Designer CNTs can remarkably enhance contaminant removal efficiency and facilitate nanomaterial recovery and regeneration. An increasing number of CNT-based materials have been used to treat diverse organic, inorganic, and biological contaminants. These success stories demonstrate their strong potential in practical applications, including wastewater purification and desalination. However, CNT-based technologies have not been broadly accepted for commercial use due to their prohibitive cost and the complex interactions of CNTs with other abiotic and biotic environmental components. This paper presents a critical review of the existing literature on the interaction of various contaminants with CNTs in water and soil environments. The preparation methods of various designer CNTs (surface functionalized and/or modified) and the functional relationships between their physicochemical characteristics and environmental uses are discussed. This review will also help to identify the research gaps

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that must be addressed for enhancing the commercial acceptance of CNTs in the environmental remediation industry.

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Contents

1. Introduction

The earth is continuously being contaminated with numerous toxic substances from both natural and anthropogenic sources. Rapid population growth and increasing industrial development have caused the discharge of various toxic elements, compounds, and/or materials into the environment. Many new chemicals have been introduced for use without proper assessment of their environmental risks and human health impacts. The discharge of untreated industrial effluent into water and soil, the indiscriminate use of pesticides and fertilizers in agriculture, the unregulated use of harmful chemicals in consumer products, the lack of proper public sanitation systems in developing countries, the combustion of fossil fuels, the weathering of toxic elements from rocks and minerals, and the over-extraction of ground water are some of the primary causes of contamination of water, soil, and air. This environmental issue is worsening day by day as modern society faces ever increasing cases of deaths due to diseases, such as cancer. Although industrial and agricultural growth and the use of new chemicals are necessary to maintain human civilization, the scientific community has a huge responsibility to develop effective technologies for cleaning up the environment.

The search for effective and low-cost materials that can eliminate present and future harmful contaminants and treat hazardous wastes in the environment is a scientific and technological issue of paramount importance. Scientists around the world have been searching for various materials - either of natural or synthetic origin - to fit into the purpose of environmental remediation. However, conventional materials (e.g., zeolite, clay minerals, and agricultural/industrial waste-based adsorbents) often experience drawbacks in practical applications, including (i) poor contaminant removal capacity, (ii) lack of contaminant interaction specificity, and (iii) environmental instability (Sud et al., 2008; Bhatnagar and Sillanpää, 2010; Bhatnagar et al., 2011; Sarkar et al., 2012; Perego et al., 2013). Some adsorbents prepared from industrial and municipal waste materials may also pose risks of secondary pollution (Bhatnagar and Sillanpää, 2010). In this context, carbon materials, such as activated carbon and biochar, occupy a unique position in the hierarchy of adsorbent materials for eliminating toxic substances in air, water, and soil (Mohan et al., 2014; Ok et al., 2015). Activated carbon and biochar may also encounter a number of problems when applied under the field conditions, such as poor adsorption specificity and biofouling. In addition, over the last decade, carbon nanotubes (CNTs) and graphene-based materials have seen an extensive use for environmental remediation (Mauter and Elimelech, 2008; Apul and Karanfil, 2015; Perreault et al., 2015).

In recent decades, CNTs have attracted the attention of scholars worldwide. These nanomaterials possess distinctive mechanical, electrical, thermal, and other properties that qualify them for applications in electronics, light sources, lightweight but high-strength polymer composites, sensors, nanoprobes in high-resolution imaging, nanoelectrodes, and hydrogen reservoirs (Baughman et al., 2002; De Volder et al., 2013).

This tiny crystalline form of active carbon also holds enormous potential in the field of environmental remediation, which has so far

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