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Enhanced Carbon-Based Nanomaterials for Superior Environmental Contaminant Separation

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ABSTRACT

Nanomaterials provide a unique way for the separation of contaminants from the environment by their large surface area, chemical modification capacity, and ease of regeneration. These properties make nanomaterials highly effective in removing pollutants from water and air, offering a promising solution for addressing environmental pollution. Additionally, their small size allows for easy dispersion and penetration into contaminated areas for thorough removal of contaminants. They have a lot of surface area, can be recycled, and are easy to desorb metal ions from while still being able to absorb them. This makes them easier to chemically change and recycle, which is why they are often used for cleanup. Furthermore, carbon nanoparticles may be easily mixed with other nanomaterials and functionalized, resulting in a multifunctional nano adsorbent. For remediation, nanomaterials primarily rely on the use of various methods such as adsorption, chemical modification, and filtration. Additionally, carbon nanoparticles have shown promising results in the removal of organic pollutants due to their high adsorption capacity and efficiency. By combining different nanomaterials, researchers can enhance the remediation process by targeting a wider range of contaminants. We have discussed current advances and the uses of carbon nano composites in the treatment of heavy metal-contaminated environments, as well as their use in environmental remediation, in this article. Carbon nano composites have shown great potential in removing heavy metals from contaminated environments due to their high surface area and reactivity. Additionally, their versatility in being combined with other nanomaterials allows for tailored solutions to specific remediation challenges.

Key words: *Carbon Nanomaterials, Environmental Remediation, Adsorption Capacity, Heavy Metal Removal, Nanocomposites*

Introduction

Nanotechnology is an advanced scientific field that may address several environmental issues by changing the size, structure, and toxicity of materials (Al-Senani and Al-Fawzan, 2018). Nanomaterials are being progressively utilized for the purpose of eliminating various types of pollutants from the environment. These pollutants include carbon-based substances, biological contaminants, and heavy metals. The reason for their growing utilization lies in their large surface area, ability to undergo chemical modifications, and ease of regeneration (Bozbaº and Boz, 2016; Bradder *et al*., 2011; Brunet *et al*., 2009).

Carbon nanoparticles are special because they are non-toxic, have a high surface area to volume ratio, break down quickly, and are especially good for cleaning up the environment. The efficacy of these carbon nanostructures in filtering water polluted with heavy metals has been demonstrated. This is a grave matter that endangers people's well-being. According to the results of this literature review, carbon nanostructures exhibit exceptional physicochemical characteristics and hold significant promise for addressing environmental issues and purifying water (Baby *et al*., 2019). The uses of carbon nano composites in the handling of contaminants from the environment as well as their use in environmental remediation are discussed in this article. Carbon nanomaterials are categorized based on their dimensions (Bhattu and Singh, 2023).

Carbon nanomaterials, such as carbon nanotubes (CNTs), fullerene, graphene, graphene oxide, and activated carbon, are being studied for their potential in cleaning up heavy metal contamination in the environment. Their success can be attributed to their attractive characteristics, including their high surface-to-volume ratio, recyclability, and ability to easily release the adsorbed heavy metals. Regeneration just necessitates the application of a mineral acid solution (Tiwari *et al*., 2012) (Table 1). Carbon nanoparticles, with their high surface-to-volume ratios and ease of recycling, have shown potential in eliminating heavy metals from polluted water sources, making them a practical choice for sustainable pollution cleaning projects (Ahmed, 2022).

Carbon nanoparticles have considerable promise for extracting heavy metals from water because of their extensive surface area, nanoscale dimensions, and varied functionalities. An effective technique for incorporating carbon nanoparticles into water treatment involves adsorption, wherein the heavy metals are drawn to the surface of the nanomaterials and then eliminated from the water. Moreover, these materials may be readily modified with various groups to augment their ability to adsorb certain heavy metals (Devi *et al*., 2023; Hussain *et al*., 2021).

Different Types and Properties of Nanomaterials

Carbon nanoparticles are becoming increasingly popular due to their exceptional physicochemical characteristics, which may be utilized to more efficiently treat water polluted with heavy metals. In addition, they are more readily amenable to chemical modification and recycling. Furthermore, carbon nano particles has the ability to readily integrate with other nanomaterials and undergo fictionalization, leading to the creation of a versatile nano adsorbent with many functionalities. Nanomaterials are structures that have diameters ranging from 1 to 100 nanometers (Saleh and Gupta, 2016). Due to their higher surface area to volume ratio and quantum effects, nanomaterials behave differently than bulk materials (Ding and Kuhlbusch, 2017). Carbon-based nanomaterials, characterized by high strength, thermal and electrical conductivity, are highly sought after in engineering, science, and medicine for applications in electronics, medicine, and environmental science (Nasir *et al.,* 2018). Carbon nanotubes (CNTs) are usually made with arc discharge or graphite chemical vapour deposition (CVD)(Duc Vu Quyen, 2019). Carbon nanotubes (CNTs) are durable, long-lasting materials with exceptional strength, resistance to high temperatures, and excellent electrical and thermal conductivity, making them suitable for various applications (Kim, 2017). A 2D sheet of sp2 hybridized carbon atoms arranged in a hexagonal lattice makes up graphene. It is an organic substance (Siqueira, 2017). The toughness, flexibility, and ability to mix with other substances make graphene a very appealing alternative for many uses (Kulkarni, 2015).

Table 1. Dimensions and examples of carbon nanomaterials are structure.

Sr No	Dimensional structure	Dimensions in nm	Examples
1	Zero dimension (0-D)	Less than 100 nm	Fullerene and quantum dots (Han *et al*., 2016)
2	One dimension (1-D)	One dimension structure is greater than 100 nm	Carbon nanotubes and titanium nanotubesnanoribbons, nanobelts, nanotubes, nanorods, and nanowires (Lee *et al*., 2014)
3	Two dimension (2-D)	Two dimensions more than 100 nm	nanodisks, nanowalls, nanosheets, nanoplates, and nanoprisms, Graphene (Singh, 2011)
4	Three dimension (3-D)	All dimensions greater than 100 nanometers	Nanomaterial composites, Nanoflowers, nanopillars, nanocones, nanocoils, and nanoballs.

Remediation of environmental pollutant using carbon nanomaterials

Fullerenes are effective nanomaterials for adsorbing species by allowing adsorbates to pass through carbon nanoclusters, due to their low aggregate tendency and flaws (Kaneko, *et al*., 1993; Lucena *et al*., 2011). Alekseeva *et al*. (2016) found that fullerenes absorb Cu^{2+} ions, as per the Langmuir model, when compared to nanocomposite-polystyrene films for their removal of the ion (Alekseeva, 2016). In the initial situation, it was found that fullerenes have a greater capacity for removing Cu^{2+}. Diana and her colleagues built a nanoscale multilayered microbot using carbon materials, specifically graphene oxide, nickel, and platinum. This surface served distinct purposes, including the entrapment of Pb^{2+} ions in graphene oxide, the control of microbots inside the intermediate layer of Ni by an external magnetic field, and the facilitation of motor movement in the inner layer of platinum (Vilela *et al*., 2016). Yang and colleagues synthesized hydrogen microspheres using a combination of graphene oxide and sodium alginate (GO-SA). These microspheres were then used to efficiently absorb Mn2+ ions from an aqueous solution, with a capacity of 56.49 mg/g (Yang *et al*., 2018). Mousavi *et al*. (2018) fabricated graphene oxide nano composites with magnetite characteristics, achieving 98% removal efficiency and a high capacity of 126.6 mg/g, showing antibacterial properties against Streptococcus mutans and Pb2+ ions (Mousavi *et al*., 2018). The maximum record of Pb2+ ion removal over functionalized graphene at pH 5.0 in 40 minutes was achieved (Thakur *et al*., 2017). The rate of adsorption of Pb2+ ions was improved by graphene-hydrogel with sulfonate synthesized nano composites with oxygen-containing functional groups, resulting in a highly polar interface with a high productivity of 1308 mg/g and equilibrium achieved in less than 40 minutes (Zhang Chao-Zhi, *et al*., 2018). Scientists developed magnetic graphene oxide to quickly extract and separate Fe (II) and Mn (II) from micro polluted freshwater. Toxic metal ions were successfully removed using graphene-based adsorbents (II) (Yan *et al*., 2014). The use of carbon nanotubes to decontaminate cationic methylene blue (MB) from an aqueous solution has been extensively studied (Ali, *et al.*, 2018). The composite material, made of MWCNTs and Fe2O3 nanoparticles, shows promising results in eliminating neutral red and methylene blue with adsorption capacities of 42.3 and 77.5 mg/g, respectively (Figure 1) (Huaiyu *et al*., 2010).

Carbon nanotubes (CNTs) have shown efficacy in adsorbing harmful and carcinogenic trihalomethanes (THMs) from water after purification using an acid solution. Their high surface area and unique structure make them a promising solution for water treatment plants, allowing them to efficiently remove harmful contaminants (Lu *et al*., 2005). PANI/MWCNTs have a significant adsorption capability for effectively removing aniline and phenol from large volumes of aqueous systems. They can be easily separated and recovered from the fluid using a magnetization solution, making them suitable for water treatment plants seeking efficient removal of hazardous chemicals (Shao *et al*., 2005). The adsorption capacity of graphitized carbon nanotubes (CNTs) is 30.8 milligrams per gram (mg/g), whereas the adsorption capacity of pure CNTs is 28.7 mg/g. They achieved an exceptional adsorption capacity of 132.6 mg/g at a temperature of 310 K (Shahryari *et al*., 2010). Cd2+ adsorption was more electro statically promoted in MW/H_2SO_4/$KMnO_4$ modified CNTs than in MW/H_2SO_4 modified CNTs due to the negative charges on the surface (Kuo *et al*., 2008). Cerium nanocomposites based on aligned CNTs, known as CeO2/ACNTs, have been created as a novel Cr(VI) adsorbent for drinking water at pH 7.0. The greatest adsorption capacity of CeO2/ACNTs was 30.2 mg/g (Di *et al*., 2004). Polyacrylic acid was used to modify MWCNTs surface for europium absorption, while refined iron oxide magnetite improved decontamination, purification, and recovery processes (Chen *et al.,* 2009).

The nano composite films of single-walled carbon nanotubes (SWCNT) and titanium dioxide (TiO2) were fabricated by applying a sol-gel technique to deposit TiO2 onto an extremely thin network layer of SWCNT. The exclusive utilization of GO as the adsorbent has several limitations, including challenges in retrieval and reusability, potential environmental hazards owing to biotoxicity, and other related issues. Host elements were included in the composite GO in order to accomplish these objectives. Indeed, GO had significant potential in many environmental applications. However, composite materials consisting of substract and catalyst surpassed GO in terms of adsorption capacity, batch kinetics, and other performance measures (Tahir *et al*., 2019)

GO/1-OA, catalyzed Go, demonstrated excellent surface assimilation for pollutants, with hydroxyl, epoxy, and carboxylic functional groups acting as active anchoring sites for heterogeneous Ag^+ ion nucleation (Wang *et al*., 2013). Hybridization with GO sheets revealed tetrahedral Ag_3PO_4 structures that had undergone morphological transition from rhombic dodecahedrons (Wang *et al*., 2017).

Discussion

Nanotechnology is a promising scientific field that can address environmental issues by altering material size, structure, and toxicity. It could be used to create efficient water filtration systems, biodegradable materials, and clean up oil spills, thereby reducing waste and removing pollutants from the environment (Karn *et al*., 2009). Further research is needed to optimize their performance and scale up their application for real-world environmental remediation. This article discusses recent advancements in using fullerenes, carbon nanotubes, graphene, graphene oxide, and activated carbon for the separation of heavy metal from the environment. These materials have shown promising results in removing heavy metals due to their unique properties such as high surface area, strong adsorption capacity, and chemical reactivity. Future research should focus on optimizing the synthesis methods and exploring new applications for these nanomaterials in environmental remediation.

Carbon nanoparticles are non-toxic, high surface area to volume ratio, and quickly break down, making them ideal for environmental cleaning. They effectively filter heavy metal-polluted water, a concern threatening human health. These nanostructures have exceptional physicochemical characteristics, demonstrating their potential for addressing environmental issues and water purification (Liu *et al*., 2008). This article explores the advancements in carbon nanocomposites' use in environmental contaminants handling and remediation, categorizing them based on their dimensions, and their potential applications in environmental remediation. This article explores the use of carbon nanocomposites in environmental remediation and handling contaminants. Carbon nanomaterials are categorized into zero-dimensional, one-dimensional, two-dimensional, and three-dimensional structures, each with unique properties that can be utilized in various applications in environmental science and engineering (Bhattu and Singh, 2023).

This article examines the utilization of carbon nanomaterials, such as carbon nanotubes (CNTs), fullerene, graphene, graphene oxide, and activated carbon, in the environment, specifically in the

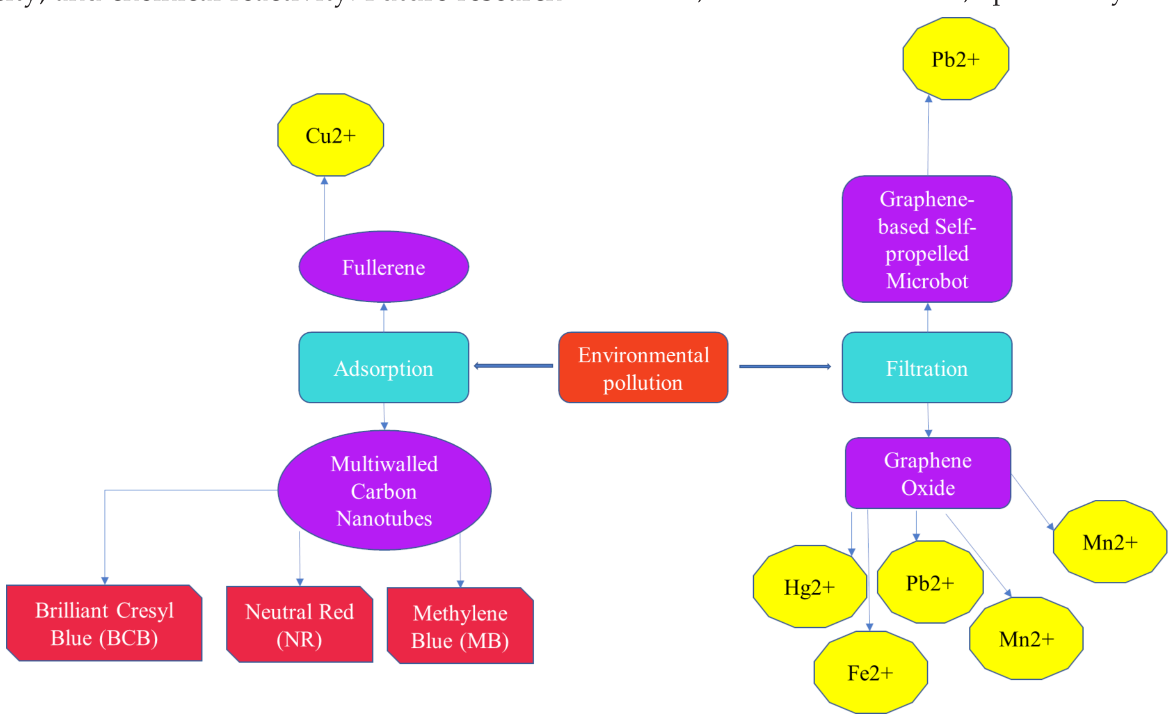

Fig. 1. Role of carbon nanomaterials in separation of environmental contaminants.

remediation of heavy metal contamination. Their popularity can be attributed to their attractive characteristics, including a high surface-to-volume ratio, simplicity of recycling, and the ability to easily release the adsorbed heavy metals. Regeneration just requires a mineral acid solution. Carbon nanoparticles have demonstrated significant promise in eliminating heavy metals from polluted water sources, offering a viable answer for environmental rehabilitation endeavors. Due to their high efficiency and cost-effectiveness, they are a practical choice for sustainable pollution cleaning projects (Tiwari *et al*., 2012; Ahmed, 2022). Moreover, carbon nanomaterials have shown great efficiency in removing heavy metals such as lead, cadmium, and arsenic from water sources. Their versatility and effectiveness make them a promising solution for addressing water contamination issues caused by heavy metal pollutants (Devi *et al.,* 2023; Hussain *et al*., 2021). Carbon nanoparticles are gaining popularity due to their efficient treatment of heavy metal-polluted water, chemical modification and recycling capabilities, and their ability to integrate with other nanomaterials, creating versatile nanoadsorbents (Saleh and Gupta, 2016).

Carbon nanoparticles, such as carbon nanotubes and graphene, are gaining popularity due to their ability to treat heavy metal-polluted water, be easily reusable, and integrate with other nanomaterials for functionalization, making them valuable in various industries (Saleh and Gupta, 2016; Kim, 2017). According to their observations, Rodrguez *et al*. (2010) determined that MWCNTs had the ability to effectively remove both cationic and anionic dyes from water (Qu *et al.,* 2008). Furthermore, significant endeavor is being dedicated to the development of very portable and highly hydrophilic membranes for the purpose of treating contaminated wastewater generated by both industrial and home sources, as well as refining crude oil and gasoline. Scientists fabricated a highly slender and flexible membrane by employing Ultraviolet rays to irradiate a nanopolymer network composed of Single-Walled Carbon Nanotubes (SWCNT) and Titanium Dioxide (TiO2) (Gao, 2014). Wang *et al*. (2015) found that GO aptamer such poly (vinyl alcohol) (PVA) improved the molecule's mechanical properties, shape, and pore structure (Wang *et al*., 2015; Huang *et al*., 2018). The nanofiber membranes should be put to the test over a long length of time, under the mechanical, thermal, and chemical conditions that would be encountered in real-world scenarios and with realistic wastewater models (Saleem and Zaidi, 2020).

Conclusion

The development of enhanced carbon-based nanomaterials, like single-walled carbon nanotubes (SWCNTs) and graphene oxide (GO) composites, has revolutionized environmental contaminants separation. These materials offer superior adsorption capacities, faster batch kinetics, and improved reusability compared to traditional adsorbents. The incorporation of host elements and catalysts further enhances their effectiveness, making them highly efficient for various environmental applications. These nanocomposites are promising for long-lasting and effective removal of contaminants in environmental engineering, addressing issues like biotoxicity and retrieval difficulties. These innovations highlight the potential of carbon-based nanomaterials in providing efficient and sustainable solutions for environmental purification.

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Conflict of interest

Authors declare that no conflict of interest occurs.

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