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Harnessing the power of graphene nanocoating materials: Innovative solutions for wastewater remediation

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ABSTRACT

The rise of nanocomposite coatings, valued for their multifunctional properties addresses the escalating contamination of air, water, soil, and aquatic ecosystems driven by industrialization, population growth, and urbanization. Graphene oxide-based nanocomposite materials are particularly effective in water and wastewater treatment, leveraging their high surface area, mechanical strength, and functional adaptability. The review highlights the use of graphene nanocoating for pollutant adsorption and photodegradation, emphasizing their affordability, scalability, efficiency, and reusability. These materials can remove or significantly reduce over 90% of heavy metal ions and hazardous contaminants from wastewater, offering a potent solution for environmental remediation through hybrid nanocomposites based on graphene.

KEYWORDS

Graphene nanocoating; Pollutant adsorption; Graphene oxide; Water treatment

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Introduction

The contamination of air, water, soil, and aquatic ecosystems is continuously rising due to rapid industrial development, growing global population, intensifying agriculture, and urbanization, which has drawn significant political and scientific attention to the issue [1]. The environmental impact of pollutants released from industrial processes, agricultural practices, and synthetic compounds, including cosmetics and medications, can be substantial, posing a risk to both humans and animals [2]. Acute exposure to untreated wastewater disposed of in rivers, lakes, and other freshwater bodies can pose significant health risks to humans and threaten the existence of aquatic life and the surrounding environment. Therefore, there's been a lot of interest in developing novel adsorbents to manage pollution [3,4].

Nanocomposite coatings are materials with at least two immiscible phases that can be separated by the interface region of usage in order to provide them with improved mechanical properties that make them stiff, high wear, deterioration resistance and good adsorbents [5]. Graphene (Gr), the latest discovered Sp^2 hybridized carbon allotrope, exhibits unique properties primarily due to its two-dimensional hexagonal lattice structure. Ever since Geim and Novoselov (2004) isolated and characterized graphene, the wonder material, it has generated a lot of attention in both academic and business circles [6]. It possesses unique properties like the quantum Hall effect, high carrier mobility at room temperature (~10,000 cm^2/Vs), and a large effective surface area (2630 m^2/g). It also has a high Young's modulus (~1 TPa), excellent optical transparency (~97.7%), and exceptional thermal conductivity (3000-5000 W/mK). These characteristics make it a material of great interest for various applications [7].

Additionally, graphene's large surface area (2630 m^2/g) offers plenty of active sites for the adsorption of pollutants and promotes interaction between the photocatalyst and the target pollutants, improving the rate of degradation. This makes graphene a viable approach to efficient environmental remediation. Furthermore, graphene oxide (GO) and reduced graphene oxide (rGO), graphene's equivalents, are also essential. Their enhanced adsorption capability, modifiable attributes, and suitability for Aqueous environments enhance their photocatalytic efficacy, rendering them efficacious for the remediation of environmental pollutants.

Graphene has several unique properties, such as being impermeable to gases, resistant to chemicals (acids, bases, and salts), possessing antibacterial potential, thermal stability, eco-friendliness, and, most notably, a high specific surface area [8-10]. Additionally, the flexible surface chemistry of graphene, combined with these valuable properties, offers a promising area for research aimed at enhancing the performance of protective surface coatings [11].

Numerous recent reviews have been published on the structure, synthesis, chemistry, and different applications of graphene, but very few of them specifically address graphene composite nanocoating for environmental concerns. In this review, our goal is to illustrate the synthesis processes, characterization, properties, and application of graphene nanocoating materials in pollution management with a focus on wastewater remediation.

Synthesis Method of Graphene Nanocoating Material

Recent studies have focused on creating graphene layers using various techniques, emphasizing the importance of surface properties and structural customization. Developing functional graphene-based coatings is thought to depend heavily on graphene's surface properties and its ability to be customized structurally [12]. The architectures and characteristics of graphene-based materials are greatly influenced by the production techniques utilized to develop them.

Graphene-coated materials are made using top-down and bottom-up techniques. Top-down methods involve

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mechanical, liquid-phase, oxidation, and electrochemical exfoliation processes. Bottom-up techniques use organic precursors, including chemical vapor deposition (CVD), epitaxial growth, and chemical reactions. CVD, for instance, decomposes carbon-containing gas at high temperatures to create uniform, high-quality coatings for electronics. Composite photocatalysts are formed by combining graphene with semiconductors like metal oxides (e.g., TiO_2, ZnO) or carbon compounds like CNTs [13,14]. These composites leverage the synergy between graphene and other materials to enhance photocatalytic efficiency, aiding in the breakdown of environmental pollutants (Figure 1).

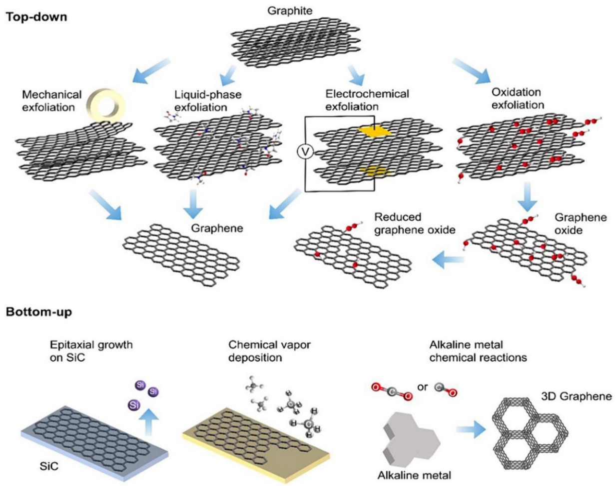

Figure 1. Graphene synthesis methods: top-down and bottom-up for various applications [13].

Properties of Graphene Nanocoating Material

Nano-materials can significantly enhance mechanical properties by offering benefits such as reducing defects or cracks at the nano-scale when incorporated into composites [15]. Because graphene is flexible, graphene coatings can adapt to the substrate surface's curve and roughness. Graphene's aromatic C=C bond network spreads over the basal plane due to the delocalization of the electron cloud, giving the material thermal stability. The addition of functional groups and imperfections to graphene improved its wettability and electrochemical activity, making it a viable material for electrochemical applications [16]. Given that GO has high mechanical properties, it has been studied as a nano-filler for reinforcement in a variety of biomedical applications [17].

While converted into bulk materials, graphene-based 2D materials have a propensity to stack during the composites and aggregate synthesis process. The poor interfacial behaviour between graphene layers and polymeric matrix causes this behaviour, which lowers the thermal, electrical, and mechanical properties of graphene-based composites. The interfacial contacts between fibers and matrices may be strengthened by graphene [18].

The orientation of the graphene within the composites determines its thermal conductivity [19]. A monolayer of graphene was found to have a specific surface area of 2630 m^2/g, an aspect ratio of more than 2000, and a thermal conductivity evaluation of 5300 W/mK—all of which were significantly higher than that of any other material.

Graphene-based materials exhibit unique optical properties, enabling the development of optical devices and biosensors. These are categorized into surface plasmon resonance (SPR), spatial light-based, and graphene-based optical fiber sensors. They are used for detecting single cells, anti-cancer drugs, antigen-antibody interactions, proteins, and cell lines. Researchers have emphasized the high-performance capability of graphene-based SPR optical biosensors to detect changes in the graphene surface structure and related biomolecular interactions [20,21].

Characterization of Graphene Nanocoating Material

Understanding the performance and possible uses of graphene nanocoating materials requires a thorough assessment of their structural, chemical, and physical characteristics. For the purpose of evaluating the quality and flaws in the graphene structure and gaining knowledge about the crystalline nature and layer number of the material, methods like Raman spectroscopy are essential [22].

Surface topography and morphology of graphene nanocoatings are examined using scanning electron microscopy (SEM) and atomic force microscopy (AFM), which reveal coating thickness and uniformity [23]. The crystalline structure is analyzed through X-ray diffraction (XRD), while elemental composition and chemical states are determined using X-ray photoelectron spectroscopy (XPS) [24]. Degradation properties and thermal stability are assessed with thermal gravimetric analysis (TGA). These characterization techniques ensure graphene nanocoatings meet necessary standards for various applications, including protective barriers, electronic devices, thermal management, and corrosion resistance [25].

Application in Environmental Remediation

Graphene and its analogues are emerging materials in nanotechnology, showing great promise in water purification through membrane technology. The adsorption capacity depends on the adsorbent properties. Functional groups like -C=O, -COOH, -OH, and -C-O-C on graphene oxide enhance its adsorption capabilities [26]. The large surface area, numerous active binding sites, and electron-rich environment of graphene nanocomposites make them highly effective at removing various pollutants, including pesticides, heavy metals, and organic dyes. The rapid growth of industrial sectors, particularly in rural areas, leads to the release of toxic by-products into natural water sources. Photocatalytic degradation of industrial organic pollutants is another effective method for addressing this issue [27].

Heterogeneous photocatalysis encompasses processes such as organic synthesis, water splitting, photo-reduction, hydrogen transfer, disinfection, water detoxification, and the removal of gaseous pollutants. In 2D graphene nanocomposites, inorganic nanoparticles prevent graphene from aggregating, thereby maintaining high surface area and pore volume. Over the past 20 to 30 years, various metal oxide nanoparticles have been combined with graphene oxide (GO), including silver oxide, titanium dioxide, zinc oxide, copper oxide, aluminum oxide, iron oxide, and zirconium dioxide. These combinations enhance the properties of graphene, making it more effective in various photocatalytic applications [28].

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Table 1. Adsorption and photocatalytic degradation of various hazardous aquatic water pollutants.

Serial no.	Graphene composite material	Degradation pollutants	References
1	CdS–RGO	Metal ion: Cr (VI)	[29]
2	(Fe_3O_4/rGO)	Metal ions: As(V), Ni (II), and Pb (II)	[30]
3	GO-Fe_3O_4@SiO_2@CdS	Phenanthrene	[31]
4	GO-Ag_3PO_4	Naphthalene (NAP), Pyrene (PYR)	[32]
5	CuO–rGO	Rhodamine B (Rh B)	[33]
6	ZnO/rGO	Organophosphorus pesticide	[34]
7	gC_3N_4/GO/V_2O_5	Chlorpyrifos pesticide	[35]
8	(GO/Y_2O_3/NiO)	Ciprofloxacin (CIP) and amoxicillin (AMOX)	[36]

Adsorption of ionic pollutants

Ionic pollutants are found in contaminated water mostly in two forms: (i) nonmetal ions such fluoride, phosphate, nitrate, and sulphide, and (ii) metal ions including arsenic, mercury, cadmium, chromium, cobalt, copper, selenium, and lead. While functionalized graphene was first used as an ionic water remediation adsorbent. Chandra et al. demonstrated arsenic which exists as arsenite and arsenate ions is one of the most toxic and carcinogenic chemical elements can be easily removed from contaminated water [37]. Sreeprasad et al. used a redox-like reaction between GO and the metal precursors to create rGO–metal/metal oxide composites such as Ag–rGO and MnO2-rGO, which removed Hg (II) from water very well [38].

Photocatalytic degradation of organic pollutant

Graphene-based nanocomposite materials are effective in adsorbing organic pollutants like dyes, gasoline, and polycyclic aromatic hydrocarbons (PAHs) through physisorption [39]. Fan et al. demonstrated that a magnetic chitosan–reduced graphene oxide (rGO) composite material enhances the adsorption of methylene blue (MB) from water due to electrostatic interactions between charged amino acid groups and MB. Bai et al. improved the photocatalytic degradation of PAHs by combining titanium dioxide (TiO_2) with graphene (GR-TiO_2, 2.5 wt% graphene) [40]. This composite achieved significantly higher degradation rates of 68%, 78%, and 85% for phenanthrene (PHE), fluoranthene (FL), and benzo[a]pyrene (BaP), respectively, under UV light, compared to 48% for PHE and 54% for FL with TiO_2 alone. Graphene oxide (GO) acts as an electron reservoir, inhibiting electron-hole recombination and enhancing the production of reactive oxygen species, thereby improving PAH breakdown. This demonstrates the potential of graphene-based nanocomposites as effective photocatalysts for PAH degradation (Figure 2) [41].

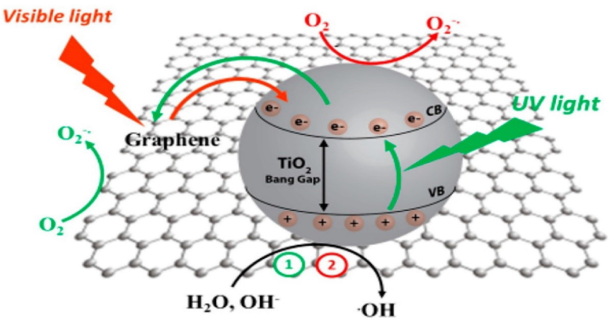

Figure 2. Mechanisms of UV and visible light activation of TiO_2 with graphene [42].

Removal of antibiotics

Antibiotics are becoming more and more necessary for treating bacterial illnesses in both humans and animals, and their application in agriculture is growing. As a result, antibiotics are now widely distributed and can be found in a variety of aquatic habitats [43]. Soltani and group eliminated triclopyr from a solution containing tetracycline (TC) by employing a visible-light-induced BiVO4/rGO nanocomposite produced by ultrasonic methods [44].

Disinfection of biological pollutants

Moreover, there are different types of microorganisms found in wastewater, including viruses, bacteria, fungi, algae, amoebas, and plankton, are accountable for an array of disease. Since, GO has the advantage of having antibacterial qualities and being biocompatible, a two-phase method including water and toluene has been developed by Liu et al. to produce self-assembling TiO_2 nanorods on GO sheets [45]. The authors demonstrated significantly better antibacterial activity against E. coli cells using this technique.

Conclusions

This research emphasizes the potential application of graphene nanocoating materials in wastewater treatment by utilizing their distinct characteristics, including high surface area, mechanical strength, electrical properties, and thermal conductivity. he integration of graphene and its derivatives, like graphene oxide (GO) and reduced graphene oxide (rGO), into nanocomposites has shown enhanced photocatalytic degradation of pollutants, making them highly effective in water purification. Advanced synthesis techniques, including chemical vapor deposition (CVD) and exfoliation methods, have facilitated the production of high-quality graphene nanocoatings with tunable properties for various applications. Characterization techniques like Raman spectroscopy, SEM, AFM, and XRD are crucial in assessing these materials' structural and chemical attributes, ensuring their effectiveness in environmental applications.

Future research should focus on scalable and cost-effective production methods, novel functionalization and hybridization techniques, comprehensive studies on environmental impact and safety, exploration of multifunctional applications, and integration with existing water treatment technologies. By addressing these issues, graphene nanocoatings will be used more effectively in environmental remediation, advancing sustainable technologies that safeguard human health and natural resources.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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