

Application of Graphene and Its Derivatives in Environmental Management

Shutong Chen

Henan University, Zhengzhou, Henan Province, 450000, China
tsc67968@gmail.com

ABSTRACT

Graphene, a novel nanomaterial, has demonstrated promising applications in environmental management due to its unique physicochemical properties. This paper reviews the practical applications of graphene in water treatment, air purification and waste management. In water treatment, graphene oxide has shown high efficiency in removing heavy metal ions and organic pollutants. In air purification, graphene-based catalysts exhibit excellent removal efficiency for nitrogen oxides and sulfur dioxide, while graphene oxide also performs exceptionally well in removing volatile organic compounds. Additionally, graphene's applications in waste management, including electrochemical waste treatment and thermal conductivity in waste incineration, highlight its potential in improving treatment efficiency and reducing harmful gas emissions. Despite the promising outlook for graphene in environmental improvement, challenges such as high production costs and long-term stability issues need further investigation. Future research should focus on reducing production costs, enhancing material performance, and assessing environmental impacts to facilitate the widespread application of graphene in environmental protection.

KEYWORDS

Graphene; Environmental Management; Water Treatment; Air Purification; Waste Management; Graphene Oxide; Graphene Catalysts

1. INTRODUCTION

Graphene, a two-dimensional material composed of a single layer of carbon atoms, has garnered widespread attention since its successful synthesis due to its outstanding physical and chemical properties. Not only does graphene exhibit extremely high electrical conductivity, thermal conductivity, and mechanical strength, but it also possesses excellent optical transparency and chemical stability. These characteristics make it highly promising for environmental improvement. This paper will delve into the applications of graphene and related materials in water treatment, air purification, and waste management, analyzing their effectiveness and discussing future development trends and challenges.

2. APPLICATIONS OF GRAPHENE IN WATER TREATMENT

Water treatment is a critical area of environmental protection, and the introduction of graphene has brought revolutionary changes to water treatment technologies. Below are several important applications of graphene materials in water treatment.

2.1. Application of Graphene Oxide (GO) in Removing Contaminants from Water

Graphene oxide (GO), due to its high specific surface area and excellent functionalization capabilities, is widely used in water treatment. GO can effectively remove heavy metal ions, dyes, and organic pollutants from water. Studies have shown that the specific surface area of GO can reach up to 2630 m²/g, providing it with exceptional adsorption capacity. In 2019, research by Meng et al. demonstrated that GO, as an adsorbent, can remove inorganic pollutants like heavy metal ions through chelation via its abundant oxygen-containing functional groups, which interact with the metal ions through electrostatic forces. Organic pollutants are removed through interactions with GO's electrons, including stacking, hydrophobic interactions, van der Waals forces, and Lewis acid-base interactions. The adsorption process is significantly influenced by the surface characteristics of the adsorbent, the nature of the pollutants, the pH of the water, and environmental conditions. [1] Additionally, GO has a high removal capability for radioactive substances such as cesium and strontium, making it suitable for treating nuclear waste.

2.2. Application of Graphene Oxide Membranes in Water Filtration

Research by Wang et al. indicates that graphene oxide membranes, as a new type of water filtration material, exhibit excellent filtration performance due to their single-layer thickness and high porosity. [2] Liu and Gu's research team found that graphene membranes can effectively filter out fine particles and contaminants from water, with a flux rate reaching 70 L/(m²h), significantly higher than that of conventional membrane materials. The high selective permeability of graphene membranes enhances water treatment efficiency in processes such as reverse osmosis and nanofiltration. Additionally, graphene oxide can improve the performance of existing water filtration membranes, including mechanical strength, thermal stability, water flux, contaminant retention rate, selectivity, as well as resistance to fouling and chlorine. However, graphene oxide membranes tend to swell and delaminate in water, requiring cross-linking agents or incorporation into polymer membranes to maintain stability. [3] In summary, the unique physicochemical properties of graphene oxide and membrane technology indicate a substantial application potential and development value in the field of water treatment.

3. APPLICATIONS OF GRAPHENE IN AIR PURIFICATION

Air pollution is a global environmental issue, and the introduction of graphene has provided new solutions for air purification technologies. Here are several applications of graphene in air purification.

3.1. Application of Graphene-Based Catalysts for Removing Nitrogen Oxides and Sulfur Dioxide

Due to its excellent electrical conductivity and large specific surface area, graphene can effectively promote photocatalytic reactions to remove nitrogen oxides and sulfur dioxide from the air. [4] By creating surface defects or modifying the surface of graphene, its electronic and atomic structures can be altered to enhance its catalytic activity for reducing air pollutants. Using graphene as a catalyst support not only increases the conductivity of the catalyst but also synergistically enhances the activity of metal-based catalysts while retaining its own advantages. [5] Catalysts containing graphene have been shown to increase the removal rate of nitrogen oxides to over 85% under UV irradiation and achieve a 90% removal rate for sulfur dioxide. These catalysts not only accelerate the reaction rate but also reduce the formation of harmful by-products.

3.2. Adsorption of Volatile Organic Compounds (VOCs) Using Graphene Oxide Composites

Currently, the most common method for treating volatile organic compounds (VOCs) in the air involves using titanium dioxide as a photocatalyst to decompose these compounds. While titanium dioxide is cost-effective, stable, chemically inert, and has excellent photocatalytic properties, its high band gap limits its photocatalytic performance. Graphene oxide, with its high specific surface area and good chemical stability, can be doped with titanium dioxide to enhance its photocatalytic performance. UV-visible spectroscopy results show that doping with graphene oxide indeed improves the absorption of visible light by titanium dioxide. Analysis indicates that the doped titanium dioxide predominantly consists of anatase phase with a particle size of about 10 nanometers, smaller than pure titanium dioxide. Additionally, C1s XPS data reveal a reduction in oxygen-containing groups in the graphene oxide during the composite preparation, indicating a reduction phenomenon. [6] The results suggest that graphene oxide composites can effectively remove VOCs such as formaldehyde, benzene, and ammonia from the air, providing significant application value in industrial emission control and indoor air quality improvement.

3.3. Application of Graphene Sensors in Air Quality Monitoring

Graphene sensors are widely used in air quality monitoring due to their high sensitivity and fast response time. Studies show that graphene sensors can detect pollutant concentrations in the air in real-time and provide accurate data. This data is crucial for air pollution control and policy making. [7] Xiao's research developed a humidity sensor using graphene materials, which exhibited a 6.9 dB change in optical power in high humidity areas (relative humidity (RH) of 70%-95%). The sensor showed a linear response to humidity changes with a correlation coefficient of 98.2%, sensitivity of 0.31 dB/(%RH), and fast response speed with excellent reproducibility. The theoretical analysis of the sensing mechanism explains the experimental results and suggests that this graphene-based optical fiber sensor can also be applied to detect other chemical gases. [8] Such optical sensors complement graphene electrochemical sensors and promote the application of graphene in chemical sensing technologies.

4. APPLICATIONS OF GRAPHENE IN WASTE MANAGEMENT

Waste management is a crucial aspect of environmental protection, and the application of graphene can significantly enhance the efficiency and effectiveness of waste treatment. Below are some key applications of graphene in waste management.

4.1. Electrochemical (Adsorption) Applications of Graphene-Based Electrodes in Waste Treatment

Graphene-based electrodes excel in electrochemical applications for waste treatment due to their excellent electrical conductivity and chemical stability. Gao's team prepared modified graphene composites (rGO/TiO₂) using hydrothermal methods. Their research shows that the material has a three-dimensional porous structure with a specific surface area of 382.08 m²/g and a specific capacitance of 325.80 F/g at a scan rate of 0.01 V/s. The initial adsorption capacity of rGO/TiO₂ electrodes is 28.3% higher than that of pure rGO electrodes. After 10 cycles of regeneration, the waste adsorption capacity of rGO/TiO₂ electrodes decreased by only 5.87%, demonstrating better regeneration performance compared to rGO electrodes. The optimal electro-adsorption conditions for rGO/TiO₂ electrodes are an applied voltage of 2V, a flow rate of 35 ml/min, and an initial concentration of 1 mmol/L. The electro-adsorption process follows pseudo-first-order kinetics and the Freundlich isothermal adsorption model. The process mainly involves physical adsorption on heterogeneous surfaces. When used in a four-stage series, rGO/TiO₂ electrodes achieved an 86.84%

removal rate for simulated waste-contaminated water. [9] During electro-adsorption, graphene-based electrodes efficiently degrade organic waste, remove harmful substances from wastewater, and reduce by-product formation.

4.2. Thermal Conductivity of Graphene in Waste Incineration and Gasification

The high thermal conductivity of graphene makes it highly applicable in waste incineration and gasification processes. Studies indicate that graphene composites significantly enhance the thermal conduction efficiency during incineration, increasing energy utilization by approximately 30%. Additionally, graphene materials can serve as catalysts in waste gasification processes, facilitating the chemical transformation of waste and reducing harmful gas emissions.

4.3. Novel Catalysts Using Graphene Composites for Waste Treatment

As a new type of two-dimensional carbon material, graphene has advantages such as a large specific surface area, strong adsorption properties, acid and alkali resistance, and good radiation resistance. Significant progress has been made in its functionalization and related applications. In 2011, Wang Xiangke's research group at the Institute of Plasma Physics, Chinese Academy of Sciences, improved the method to prepare low-layer graphene oxide nanosheets from graphite powder. They studied its adsorption capacity for heavy metal ions in aqueous solutions and analyzed the effects of solution acidity, ionic strength, humic acid, and temperature on adsorption performance, as well as possible adsorption mechanisms. The low-layer graphene oxide nanosheets, prepared by liquid-phase chemical oxidation exfoliation, can reach several micrometers in size with a thickness of 2-3 nm, and contain abundant oxidative groups, showing excellent dispersion in aqueous solutions. These graphene oxides demonstrated significantly higher adsorption capacities for heavy metal ions compared to other known nanomaterials. Research shows that these composites can effectively catalyze the decomposition of organic components in waste, enhancing treatment efficiency and reducing harmful by-products [10].

5. CONCLUSION

Graphene, as a novel two-dimensional material, exhibits broad application potential in the field of environmental improvement due to its unique physicochemical properties. This review has summarized the practical applications of graphene in water treatment, air purification, and waste management, highlighting its significant advantages and prospects in these areas.

In water treatment, graphene oxide (GO) has been proven effective in removing heavy metal ions and organic pollutants from water, thanks to its high surface area and excellent adsorption properties. GO demonstrates high efficiency in pollutant removal and performs exceptionally well as a membrane material in water filtration. In air purification, graphene-based catalysts show high efficiency in removing nitrogen oxides and sulfur dioxide, while graphene oxide also excels in removing volatile organic compounds. In the field of waste management, graphene applications also show promising prospects. The high electrical conductivity of graphene enhances the efficiency of electrochemical waste treatment, and its excellent thermal conductivity aids in reducing harmful gas emissions during waste incineration.

However, despite the promising outlook of graphene in environmental remediation, several challenges remain. The high production cost is a major barrier to the large-scale application of graphene materials, necessitating further development of more economical production technologies. Additionally, the long-term stability and environmental impact of graphene have not been fully assessed and require in-depth research in practical applications. Furthermore, optimizing material performance, conducting economic feasibility analyses, and enhancing market acceptance are crucial issues. Future efforts should focus on addressing these challenges by reducing production costs,

improving material performance, assessing environmental impacts, and promoting the commercialization of technologies to advance the widespread use of graphene in environmental protection.

In summary, while graphene holds vast application potential, achieving its comprehensive use in environmental improvement requires overcoming technical and economic challenges. With continued research and technological innovation, graphene is expected to play a significant role in future environmental management and contribute to the achievement of sustainable development goals.

6. FUTURE OUTLOOK AND CHALLENGES

Despite its significant potential for environmental improvement, graphene still faces several challenges in practical applications. The high production cost remains a major barrier to the widespread use of graphene. Future research should focus on developing more cost-effective production methods and enhancing production efficiency. Additionally, the long-term stability and environmental impact of graphene have not been thoroughly assessed, and further studies are needed to evaluate its performance and ecological safety under various environmental conditions.

Moreover, there is still room for improvement in graphene's material properties, which can be achieved through chemical modification and the development of composite materials to enhance its effectiveness in specific applications. Technological economic feasibility and market acceptance are also crucial factors. Detailed cost-benefit analyses are required, alongside efforts to promote supportive policies and market adoption. Addressing these challenges will enable graphene to play a broader role in the field of environmental protection.

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