Study on the Photothermal Effect of Graphene Derivatives in Particulate Matter Degradation

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Abstract: Graphene derivatives, with their superior two-dimensional structure, high surface area, and excellent photothermal conversion properties, exhibit great potential in particulate matter degradation. This paper reviews the photothermal effects of graphene and its derivatives in particulate matter degradation, focusing on their structural characteristics, preparation methods, and photothermal performance. Particulate matter (PM2.5), a major air pollutant originating from industrial emissions and vehicle exhaust, poses serious threats to human health and the ecosystem. Graphene derivatives, by absorbing near-infrared light and generating localized high temperatures, can effectively promote the thermal decomposition and oxidation of particulate matter, significantly improving degradation efficiency and reducing secondary pollution. Studies show that functionalized or composite graphene oxide and reduced graphene oxide materials can further enhance the photothermal synergistic effect, making them suitable for air purification technology. Current challenges include preparation cost, large-scale application, and material stability. Future research should focus on developing green preparation processes and intelligent photothermal systems to promote practical environmental remediation. This paper provides a theoretical basis and research perspectives for the application of graphene derivatives in particulate matter degradation, guiding the development of sustainable air purification technologies.

Keywords: Graphene Derivatives; Photothermal Effect; Particulate Matter Degradation; Air Purification; Nanomaterials

1. Introduction

1.1 Research Background

Air pollution has become a major challenge in global environmental and public health. Fine particulate matter (PM2.5), with a diameter less than 2.5 micrometers, is a primary pollutant that can penetrate deep into the lungs, causing serious health risks such as cardiovascular diseases, respiratory diseases, and even cancer. Accelerated industrialization has led to continuous increases in greenhouse gas emissions and particulate matter concentrations. Classical air purification technologies, including adsorption and filtration, are capable of collecting air pollutants, but have low capacity of adsorption, danger of secondary pollution and high energy consumption [1]. In recent decades, graphene and graphene derivatives emerged as a hot issue because of two-dimensional structure of graphene, high surface areas and excellent photothermal conversation capabilities. These matters have made great strides in photocatalytic removal of organic airs pollutant and are being applied slowly to particulate matter removal. Under photothermal actions [2], graphene derivatives possess the function of strongly absorbing near-infrared rays to create localized high temperatures and propel the destruction and oxidation of particulate matter to achieve efficient pollutant pyrolyziation. Particulate matter degradation of graphene derivatives comes from initial study on photocatalysis. Graphene oxide (GO) and reduced graphene oxide (rGO) derivatives not just function as electron transport highways to inhibit photogenerated electron-hole recombination, but also enhance pollutant degradation and attachment efficiency using a photothermal process [3]. For example, GO-based composites are capable of dramatically accelerating VOCs and particulate matter degradation rate under visible light illumination, including the synergetic function of illumination-induced thermal actions and free radical oxidation. Besides, driven by nanotechnology, heterostructure structures of graphene derivatives combined with metal oxides further enhance photothermal performance and apply to water and airborne particulate matter pollution. Even if it's still in its initial study period, its application prospect of PM2.5 degradation under simulated atmospheric condition has become confirmed and provides a method for designing efficient and green air purification strategy. In-depth understanding of this aspect helps to elucidate the microscopic mechanism of the photothermal effect and lay a solid foundation for environmental recultivation [5].

1.2 Significance of the Research

The photothermal effect of graphene derivatives for particulate matter degradation was researched with great application and intrinsic values. For a start, environmentally, the work can be the harbinger of innovation in purification technology for air. The conventional method, such as mechanical filtering, is capable of collecting PM2.5 but not entirely capable of decomposing pollutions, with a resultant tendency of satiation of filtering material and ineptitude in regeneration. The photothermal effect, through localized heating induced by sunlight, not only increases the degradation efficiency but also reduces the energy input, achieving green and sustainable purification. This reduces urban haze, minimizes destruction of ecosystem induced by particulate matter, and facilitates carbon neutrality [6].

Second, it is necessary for public health protection. PM2.5 is rich in heavy metals and organic toxin; secondary long-run exposure has the ability to activate the body to secrete chronic diseases, whereas photothermal degradation can dramatically mineralize the toxic components to reduce the possibility of being secondarily emitted. Under the optimization of structural structure of graphene derivatives, portable purifying devices can be developed for indoor and outdoor purposes for the purpose of accelerating public health protection. Third, it facilitates interdisciplinary integration, driving collaborative innovation between environmental engineering and material science, producing high-quality talent, and supporting scientific decision-making for policy. In the long term, it will foster a system for clean air and ensure long-term development.

2. An Overview of Graphene Derivatives

2.1 Structure and Properties of Graphene

Graphene is a two-dimensional honeycomb-like crystal structure composed of a single layer of carbon atoms arranged in sp^2 hybridization. Its basic unit is a hexagonal lattice, with each carbon atom bonded to three neighboring atoms via σ bonds, forming a stable planar network. The remaining p-orbital electrons form delocalized π bonds. This structure endows graphene with extremely high mechanical strength, with a theoretical Young's modulus of up to 1.0 TPa and a fracture strength of approximately 130 GPa, far exceeding that of traditional materials like steel. Furthermore, graphene's unique electronic structure, where electrons and holes behave like massless relativistic particles at the Dirac point, results in a carrier mobility as high as 200,000 $cm^2/V \cdot s$ and enables the observation of the quantum Hall effect at room temperature. This zero-bandgap semiconductor characteristic makes it excellent for electronics, but also limits its application in certain switching devices. By controlling the number of layers, multilayer graphene can transition from the zero-bandgap state of monolayer graphene to the metallic properties of bulk graphite, further expanding its functionality. Thermally, graphene exhibits a thermal conductivity of up to 5300 $W/m \cdot K$, due to its low phonon scattering and high thermal capacity, making it promising for thermal management applications [4]. Optically, graphene absorbs 2.3% of visible light, is highly transparent, and shows broad-spectrum optical response, suitable for photodetection and transparent electrodes. The surface properties of graphene are also remarkable, with a theoretical specific surface area of 2630 m^2/g, supporting efficient adsorption and catalytic reactions. However, defects such as edges, wrinkles, or impurities in practical preparation can affect these ideal properties, leading to reduced electron mobility or thermal conductivity. Nevertheless, these defects can be modulated through functionalization to optimize applications. For example, in environmental applications, graphene's structure allows strong π-π interactions with pollutant molecules, promoting adsorption and degradation processes. The biocompatibility and low toxicity of this material further expand its potential in biomedicine, but the effects of size and surface state on cytotoxicity should be considered.

2.2 Types and Preparation Methods of Graphene Derivatives

Graphene derivatives mainly include graphene oxide (GO), reduced graphene oxide (rGO), and functionalized graphene. These are obtained by introducing oxygen-containing groups or other chemical modifications to improve the solubility and reactivity of pristine graphene. GO, the most common derivative, contains oxygen-containing functional groups such as hydroxyl, epoxy, and carboxyl groups, making it highly hydrophilic and easily dispersible in water, but sacrificing some conductivity. rGO is obtained by reducing GO to remove some oxygen groups, restoring the π-conjugated network and improving conductivity and thermal stability. Functionalized graphene, such as fluorinated or aminated graphene, introduces fluorine or amine groups for specific applications. Preparation methods are broadly categorized into top-down and bottom-up approaches. Top-down methods use graphite as the raw material, obtaining GO through mechanical or chemical oxidation exfoliation, such as the Hummers method using potassium permanganate to oxidize graphite, producing numerous oxygen groups. rGO can then be obtained through thermal or chemical reduction (e.g., with hydrazine). This method yields high quantities at low cost, but product purity is affected by the oxidation degree [7]. Bottom-up methods include chemical vapor deposition (CVD) and epitaxial growth, growing graphene on a metal substrate using a carbon source like methane, followed by transfer and functionalization to form derivatives like GO composites. The diverse types of these derivatives expand their applications; for example, GO has strong adsorption capacity for environmental remediation, while rGO has higher photo-thermal conversion efficiency. Key parameters in the preparation process, such as oxidant concentration and reduction conditions, directly affect the number of layers, defect density, and functional group distribution of the derivatives. For example, an improved Hummers method can control the oxygen content of GO to 30%-50%, optimizing its performance in photo-thermal degradation of pollutants. Functionalization methods, such as covalent bonding (esterification, amidation) or non-covalent adsorption (π-π stacking), further customize the derivatives, enabling composites with metal oxides or polymers to enhance photo-thermal effects. However, environmental impact, such as wastewater treatment, must be considered to ensure sustainability [8][9].

2.3 Photothermal Properties of Graphene Derivatives

The photothermal properties of graphene derivatives stem from their broad-spectrum light absorption capability and high photothermal conversion efficiency, particularly their strong absorption in the near-infrared (NIR) region, making them suitable for light-driven applications such as particulate matter degradation. The π-conjugated system in derivatives like GO and rGO allows electrons to transition from the valence band to the conduction band, generating heat through non-radiative relaxation after absorbing photons, with conversion efficiencies reaching over 50%. This efficiency is influenced by factors such as layer thickness, oxygen content, and size. Single-layer GO exhibits high photothermal conversion rates, while multilayer structures enhance overall absorption. Functionalized derivatives, such as PEG-modified GO, improve biocompatibility while maintaining high photothermal stability, preventing performance degradation due to aggregation. In particulate matter degradation, the photothermal effect promotes oxidation reactions through localized heating, rapidly raising temperatures to several hundred degrees Celsius, accelerating pollutant decomposition without secondary pollution [10]. Factors such as laser power density and wavelength are important; under 808 nm NIR laser irradiation, the thermal conductivity of rGO (approximately 3000 W/m·K) ensures rapid heat dissipation, enhancing degradation efficiency. Studies show that composite derivatives, such as GO-metal oxide heterostructures, further optimize photothermal properties by suppressing electron-hole recombination through interfacial charge transfer, enhancing the photothermal synergistic effect. For example, TiO2-GO composites exhibit higher heat generation rates under visible light for atmospheric particulate matter mineralization. Size control of the derivatives is also crucial; nanoscale GO sheets provide a larger surface area, promoting light absorption and heat transfer, but excessive oxidation should be avoided to prevent increased bandgap and weakened NIR response. Overall, photothermal performance is quantified by photothermal conversion efficiency (η) and temperature rise curves, with typical η values of 40%-70%, far exceeding traditional carbon materials. This offers an efficient pathway for particulate matter degradation, but optimizing the stability of the derivatives against long-term photodegradation is necessary [11][12].

3. A Review of Photothermal Effects in Particulate Matter Degradation

3.1 Sources and Hazards of Particulate Matter

Particulate matter (PM), especially PM2.5 (fine particulate matter with an aerodynamic diameter less than or equal to 2.5 μm), originates primarily from anthropogenic activities and natural processes. Anthropogenic sources include industrial emissions, vehicle exhaust, construction dust, and biomass burning, with motor vehicle exhaust and coal combustion contributing significantly to urban PM2.5 levels, often carrying harmful components such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals like lead and cadmium. Natural sources include dust storms, volcanic ash, and sea salt spray, but their contribution in urban environments is relatively minor, influenced by meteorological conditions such as wind speed and humidity. The complex composition of PM2.5, including inorganic salts, organic carbon, and elemental carbon, leads to its long atmospheric residence time and long-range transport, contributing to regional haze events. Research indicates that PM2.5 levels in industrial nations are directly correlated with energy systems, whereas in nonindustrial nations, they are more typically a function of partial combustion processes [13]. This sort of sources being a center of globe air quality regulation, its change of seasons and geographical variations from the standard acting to amplify exposure risk.

The hazards of PM2.5 largely present as systemic damages to human body. It can pass through the alveoli from the airway and blood stream to induce inflammatory responses and oxidative strain. It can provoke arrhythmia and asthmatic attack within short exposure, yet long exposure is closely associated with cardiovascular diseases, lung cancer and neurodegenerative diseases, and can even impact fetal development, causing low delivery body weight. The toxicological evidence clarifies that PM2.5-evoked cytotoxicity is caused by the generation of reactive species of oxygen and DNA damages with amplified consequences on sensitive groups of public including children and elderly [14]. Moreover, PM2.5 also inflicts indirect damages on ecology, such as acid rains and soil acidification, and damages plant photosynthetic activities and biodiversity. Epidemiological data show that globally hundreds of epidemiological mortality of millions of public are caused by exposure to PM2.5 for a year, and consequently ensure effective degradation technology to counteract its multi-aspect hazards [15].

3.2 Principle and Mechanism of Photothermal Effect

Photothermal effect means the material will absorb light energy and transform it to heat energy by non-radiative relaxation process, especially obvious for nanomaterials like graphene derivatives. Its mechanism is founded on electronic excitation and relaxation dynamics: if the energy of incident photons coincides with the spectrum of material absorption, the valence electrons will jump to the conduction band and become hot electrons. These hot electrons then rapidly relax through electron-electron scattering and electron-phonon coupling, generating localized high temperatures. The broad absorption spectrum of graphene derivatives (from ultraviolet to near-infrared) is attributed to its π-conjugated structure and defect states, and the conversion efficiency is influenced by oxygen content and layer number. For example, reduced graphene oxide (rGO) can achieve efficient photothermal conversion under 808 nm laser irradiation, with a temperature rise rate of tens of degrees Celsius per second [16]. Mechanistically, the photothermal process involves plasmonic resonance (enhanced in metal composites) and molecular vibrational excitation, ensuring heat localization rather than diffusion into the surrounding medium. In particulate matter degradation applications, the photothermal effect mechanism involves thermal-induced oxidation and free radical generation for pollutant decomposition. Hot electrons promote the dissociation of surface-adsorbed molecules, while high temperatures accelerate pyrolysis reactions, mineralizing organic components such as volatile organic compounds (VOCs). The photothermal mechanism of graphene quantum dots and other derivatives also includes quantum confinement effects, enhancing the light absorption cross-section and suppressing heat loss [17]. Furthermore, synergistic effects such as photothermal-photocatalytic coupling further optimize the mechanism, where thermal energy reduces the reaction activation energy and promotes singlet oxygen generation for oxidative degradation [18].

3.3 Research Progress of Graphene Derivatives in Particulate Matter Degradation

In recent years, efforts on the application of graphene derivatives for particulate matter degradation have garnered rapid progress, especially using their photothermal effect for efficient purification of air. Initial efforts centered on graphene oxide (GO) composites' adsorptive capacity, but the past few studies have moved towards photothermally-activated degradation, for example, GO-TiO_2 heterostructures accelerating PM2.5 oxidation under visible light illumination to levels above 90% degradation. Studies prove that three-dimensional graphene structures (e.g., aerogels) can be used as carriers for photothermal flow-by degradation of polluters for continuous flow, adaptable to waste gas destruction industrially [19]. Moreover, functionalized derivatives, for instance, N-doped rGO, reach high temperature under irradiation of the near-infrared and particulate matter surface hydrocarbon thermal decompositions and secondary pollutants' formations minimization. Developments also include experimental verification within a simulated atmosphere environment to demonstrate low-concentration PM application of the photothermal effect within. Other works step on compositive systems, for instance, combination of g-C_3N_4 with graphene derivatives to significantly enhance NO_x and VOCs degradation efficacy with photothermal-assisted photocatalysis, in which the mechanism is thermally assisted charge separate and ROS generations [20]. New developments include self-healing graphene material to be capable of repairing structural degradation damages caused along degradation processes through photothermal acts to material lifetime elongating [21]. Inasmuch as there are challenges including costs and scaling, there are emerging people on a pathway of efficient air pollution control sustenance and green-sustainability directions for the future include integrating smart photothermal systems.

4. Conclusion

The photothermal effect of graphene derivatives in particulate matter degradation offers an innovative approach to air pollution control. Its unique two-dimensional structure, high surface area, and excellent photothermal conversion properties demonstrate significant potential for efficient adsorption and thermal oxidation of particulate matter. Through the photothermal effect, graphene derivatives can rapidly generate localized high temperatures under near-infrared irradiation, significantly accelerating the mineralization of organic components in particulate matter and reducing the risk of secondary pollution. Studies show that derivatives such as graphene oxide and reduced graphene oxide, through compounding with metal oxides or functionalization, can further optimize photothermal performance and degradation efficiency, laying the foundation for developing sustainable air purification technologies. Furthermore, exploring three-dimensional graphene architectures and intelligent photothermal systems provides feasible pathways for industrial applications.

However, current research faces challenges such as high preparation costs, difficulties in large-scale production, and insufficient long-term stability. Future research should focus on low-cost, green preparation technologies, the synergistic mechanism of photothermal-photocatalysis in composite materials, and performance validation in real atmospheric environments. Through interdisciplinary collaboration, optimizing the structural design and functional control of graphene derivatives holds promise for developing efficient and cost-effective air purification solutions, which would significantly contribute to mitigating PM2.5 pollution, improving public health, and advancing carbon neutrality goals. This research not only deepens our theoretical understanding of photothermal effects but also opens new avenues for technological innovation in the field of environmental engineering.

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