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Graphene's Research Progress and Future Prospects in Sterilization and Disinfection

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Abstract. This paper systematically examines the research advancements and application potential of graphene in sterilization and disinfection. By dissecting graphene's unique physicochemical properties, it elucidates various antimicrobial mechanisms, including chemical oxidation, physical fragmentation, and disruption of the electron transport chain. Leveraging cutting-edge experimental data, it provides a comprehensive overview of the performance benefits and application contexts of pristine graphene materials, as well as graphene-metal nanoparticle and polymer composites. In response to practical challenges such as poor dispersibility, high costs, and biosafety concerns, it outlines optimization strategies and technical solutions. The study aims to offer a systematic reference for theoretical innovation and industrial utilization of graphene-based antimicrobial materials, thereby fostering technological advancements in public health.

Keywords: Graphene, sterilization and disinfection, antibacterial mechanism, composite materials, nanotechnology, biological safety

1. Introduction

In the context of sustained pressure on the global public health system, issues such as drug-resistant bacterial infections and outbreaks of emerging infectious diseases are becoming increasingly severe. World Health Organization (WHO) data indicates that approximately 700,000 deaths annually are attributed to antibiotic resistance. The misuse of traditional chemical disinfectants, including chlorine-based disinfectants and quaternary ammonium compounds, not only exacerbates the resistance crisis but also triggers secondary environmental issues like water pollution and ecological imbalance. Physical disinfection methods, such as ultraviolet light and high temperatures, are limited by weak penetration and high energy consumption, prompting the scientific community to urgently seek novel bactericidal materials that offer efficiency, safety, and environmental friendliness.

Graphene, a two-dimensional honeycomb crystal formed by a single layer of carbon atoms in sp^2 hybrid orbitals, exhibits exceptional physicochemical properties owing to its unique structural features. It boasts a theoretical specific surface area of up to 2630 m^2/g, facilitating maximum contact with pathogens. Additionally, its carrier mobility surpasses 200,000 $cm^2/(V \cdot s)$, providing a material basis for electron transfer-related sterilization mechanisms. The atomically smooth surface

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and nanoscale sharp edges grant it unique physical interaction capabilities. These attributes render graphene highly promising in the field of sterilization and disinfection. Consequently, relevant research findings have been extensively applied in areas such as medical protection, water treatment, and food preservation, positioning it as a cutting-edge focus in nanobiotechnology research.

2. Graphene's antibacterial properties

2.1. Chemical oxidation process

The chemical bactericidal effect of graphene primarily depends on reactive oxygen species (ROS)-mediated oxidative stress responses. Under illumination, electric fields, or in solution environments, ROS can be generated on the graphene surface through Fenton-like reactions or electron transfer processes. These ROS include hydroxyl radicals (·OH), superoxide anion radicals ($O_2 \cdot^-$), and singlet oxygen ($^1O_2$). These potent oxidizing agents can attack the phospholipid bilayer of bacterial cell membranes, initiating lipid peroxidation, which disrupts membrane structure and increases permeability. Additionally, ROS can covalently modify protein thiols and nucleic acid bases, leading to enzyme inactivation and DNA strand breaks. The antibacterial activity of graphene oxide (GO) is mainly attributed to its multifaceted interaction mechanisms with bacterial cells, including membrane stress, oxidative stress, and encapsulation isolation [1].

Experimental studies have demonstrated that under visible light, the production of reactive oxygen species (ROS) by graphene oxide (GO) increases by 3-5 times compared to dark conditions, significantly enhancing its bactericidal efficiency against Staphylococcus aureus. Further spectral analysis reveals that the epoxide and hydroxyl functional groups on the GO surface are crucial for ROS generation. While chemical reduction to remove some of these functional groups can improve conductivity, it diminishes the ROS production capacity, indicating a significant correlation between the chemical structure and bactericidal activity.

2.2. Mechanism by which physical action is achieved

The physical mechanism is another crucial pathway for graphene's antibacterial action, primarily involving cell membrane cutting and mechanical damage. High-resolution transmission electron microscopy (HRTEM) observations reveal that nanoscale-thick graphene sheets can act as "nano-knives," inserting into the Escherichia coli cell membrane. This disrupts the arrangement of membrane phospholipid molecules, forming holes approximately 5-20 nm in diameter, thereby causing intracellular substance leakage. Atomic force microscopy (AFM) studies show that this cutting effect is closely associated with the curvature of graphene edges, with sharp edges having a curvature radius of less than 1 nm exhibiting enhanced membrane disruption capabilities.

Additionally, graphene's high specific surface area allows it to capture a significant number of bacteria through π-π stacking and electrostatic adsorption. Studies have shown that each gram of graphene oxide can adsorb approximately 10^9 CFU of Pseudomonas aeruginosa. The mechanical stress generated during this adsorption process can cause deformation and rupture of the bacterial cell membrane. Molecular dynamics simulations reveal that when the contact area between graphene and the bacterial surface exceeds 30% of the bacterial surface area, the cell survival rate drops by more than 80%, underscoring the crucial role of physical adsorption in the bactericidal process.

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2.3. Other functions

In addition to the aforementioned mechanisms, graphene exerts antibacterial effects by interfering with bacterial physiological metabolism. Research has demonstrated that graphene competitively binds with key proteins in the bacterial respiratory chain, such as cytochrome c oxidase, thereby blocking the electron transport chain and impeding ATP synthesis. Furthermore, the interaction between graphene's surface charge and the bacterial cell membrane potential alters the conformation of membrane proteins, inhibits ion channel activity, and disrupts bacterial material transport and signal transduction.

The latest research reveals that graphene nanosheets can penetrate bacterial biofilms, disrupt their three-dimensional network structures, and expose the enclosed bacteria to bactericides. This disruptive effect on biofilms offers a novel solution to the challenge of drug-resistant bacterial infections. Experimental data demonstrate that the combination of graphene with antibiotics enhances the clearance efficiency of methicillin-resistant Staphylococcus aureus (MRSA) biofilms by over 40%. In practical applications, the antibacterial properties of graphene oxide (GO) are susceptible to various factors, including GO's morphology, structure, chemical composition, hydrophilicity, dispersibility, and the bacterial species involved [2].

3. Research on graphene-based antimicrobial materials: recent advances

3.1. Single graphene material

Monolayer graphene, characterized by its maximum specific surface area and minimum thickness, demonstrates exceptional antibacterial properties. Studies have shown that at a concentration of 0.5 mg/L, monolayer graphene can reduce the survival rate of Bacillus subtilis by 99.9% within six hours. However, in practical applications, it encounters issues such as poor dispersibility and low stability. Surface functionalization modifications, such as the introduction of carboxyl or amino groups, can enhance its hydrophilicity, but this inevitably compromises its conductivity and specific surface area.

Graphene oxide (GO) is a two-dimensional, ultra-thin carbon-based nanomaterial characterized by a surface rich in oxygen-containing functional groups such as epoxides, hydroxyls, and carbonyls. As an oxidized form of graphene (G), it possesses unique morphological dimensions and physicochemical properties, which enable it to exhibit diverse antibacterial mechanisms [3]. The abundant oxygen-containing functional groups on GO confer excellent dispersibility in aqueous solutions, making it the most extensively studied single material. Experimental data reveal that the minimum inhibitory concentration (MIC) of GO against Escherichia coli is 25 μg/mL, with its bactericidal activity positively correlated with the degree of oxidation. However, an excessively high oxidation level can compromise the material's biocompatibility. Reduced graphene oxide (rGO) retains partial bactericidal capability while significantly reducing biological toxicity, thereby enhancing its suitability for biomedical applications.

3.2. Graphene composite materials

3.2.1. Graphene-metal nanoparticle composite materials

Compositing graphene with metal nanoparticles is a crucial strategy for enhancing antibacterial properties. This composite nanomaterial integrates the bactericidal effects of metal nanoparticles with the inherent antibacterial capabilities of graphene oxide (GO), effectively addressing issues

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such as the agglomeration tendency of some metal nanoparticles [3]. For instance, in the case of silver nanoparticles-reduced graphene oxide (AgNPs-rGO) composites, the Ag^+ ions released by AgNPs can bind to bacterial DNA bases, thereby interfering with genetic material replication. Simultaneously, graphene contributes to synergistic bactericidal action through physical cutting and the generation of reactive oxygen species (ROS). Experimental results indicate that this composite material exhibits a threefold higher killing efficiency against Candida albicans compared to pure AgNPs, while significantly reducing the release rate of silver ions, thereby mitigating potential toxicity risks.

Other metal nanoparticles, such as copper, zinc, titanium dioxide, and their composites with graphene, also demonstrate excellent antibacterial properties. Research has revealed that ZnO nanoparticle-graphene composites exhibit photocatalytic activity under visible light, achieving a 98.7% removal rate of Legionella through the dual mechanisms of reactive oxygen species (ROS) generation and physical damage, thereby holding significant application potential in the field of water treatment.

3.2.2. Graphene-polymer composite materials

The composite of polymers and graphene significantly enhances material processing performance and biocompatibility. Chitosan-reduced graphene oxide (CS-rGO) composites combine the cationic antibacterial properties of chitosan with the physical bactericidal capabilities of graphene, demonstrating superior wound-healing effects in medical dressing applications. Research indicates that CS composite films with 1% rGO exhibit an inhibition zone diameter of 18 mm against Staphylococcus aureus and promote fibroblast proliferation. The antibacterial performance of GO composites can be augmented through surface modification with antibacterial organic groups. Regarding binding mechanisms, two primary methods are identified: covalent bonding and non-covalent bonding. Covalent bonding mainly involves the chemical reaction between organic molecules and the oxygen-containing groups on the GO surface to incorporate antibacterial components [4].

Polycaprolactone (PCL) and polylactic acid (PLA) biodegradable polymers, when combined with graphene, can be fabricated into 3D-printed scaffolds with antimicrobial properties. Experimental results show that PCL-rGO scaffolds exhibit no significant toxicity to bone marrow mesenchymal stem cells and inhibit the adhesion of Staphylococcus epidermidis by over 70%, thereby providing novel antimicrobial materials for tissue engineering.

4. Graphene-based antimicrobial materials: their challenges and limitations

4.1. Problem of distribution and stability

The strong π-π interactions and van der Waals forces between graphene sheets result in their facile aggregation in solvents, significantly diminishing the material's activity. Many researchers have thoroughly investigated graphene absorbers synthesized through various methods, yielding graphene powders with diverse characteristics [5]. Traditional dispersion methods, such as ultrasonication and the use of surfactants, are plagued by low efficiency and the introduction of impurities. Recent research has explored improving dispersion through non-covalent functionalization, such as incorporating pyrene derivatives via π-π stacking, and in-situ polymerization techniques. However, these methods still encounter challenges, including complex processes and high costs.

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4.2. Production costs and scaling difficulties

Currently, mainstream graphene preparation methods, such as chemical vapor deposition and oxidation-reduction, are plagued by high energy consumption, low yield, and severe pollution. For instance, the cost of producing 1 gram of high-quality graphene via the CVD method exceeds 500 USD, making it challenging to meet industrial demands. Exploring low-cost, environmentally friendly techniques, such as liquid phase exfoliation and microwave-assisted methods, has become a key research focus. However, significant breakthroughs are still required in product consistency and quality control.

4.3. Biological security and environmental hazards

Although existing studies have demonstrated that low concentrations of graphene exhibit minimal cytotoxicity to mammalian cells, high-dose exposure may induce oxidative stress and inflammatory responses. Animal experiments reveal that intravenous administration of rGO nanosheets results in diminished phagocytic function of lung macrophages in mice. Furthermore, the degradation mechanism of graphene in the environment remains unclear, necessitating a systematic evaluation of its long-term ecological impact to prevent potential nano-pollution issues.

5. Developments and outlooks

Composite Functionalization Design: Multifunctional composites with antibacterial, anti-inflammatory, and wound-healing properties are developed through the synergistic action of multiple components, meeting the demands of complex application scenarios. Intelligent Responsive Materials: Environmentally responsive antibacterial materials are prepared by combining temperature-sensitive and pH-sensitive smart materials, achieving precise and controllable bactericidal effects. Green Preparation Technology: Graphene preparation processes using biomass as raw materials are developed to reduce production costs and environmental burden. Standardized Evaluation System: Unified testing standards for antibacterial performance and assessment methods for biological safety are established to promote industrialization.

6. Conclusion

Graphene, with its unique physicochemical properties, demonstrates significant technological advantages and application potential in the field of sterilization and disinfection. Despite the current research challenges related to dispersibility, cost, and biosafety, the continuous advancements in materials science and nanotechnology are paving the way for graphene-based antimicrobial materials to achieve major breakthroughs in public health and medical care. These advancements are facilitated through innovative preparation techniques, optimized material design, and enhanced evaluation systems, thereby offering innovative solutions to the global challenges of infectious disease prevention and control.

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