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A Review of Antibacterial Properties of Graphene-Based Nanomaterials

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ABSTRACT

With the escalating challenges of global water scarcity and pollution, developing efficient, safe, and sustainable water disinfection technologies has become an urgent priority. Traditional methods like chlorine disinfection and ultraviolet sterilization face issues such as byproduct formation, spread of drug-resistant bacteria, and insufficient long-term disinfection capacity. Graphene-based nanomaterials, leveraging their unique physicochemical properties—including high specific surface area, excellent mechanical strength, and tunable electronic characteristics—demonstrate broad-spectrum antibacterial performance and biofilm resistance through synergistic effects of physical cleavage, oxidative stress, and adsorption mechanisms. Notably, they exhibit significant inhibitory effects on drug-resistant bacteria. This paper systematically reviews the antibacterial mechanisms, influencing factors, and practical applications of graphene oxide (GO) and reduced graphene oxide (rGO) in various forms and composite systems. It analyzes their performance degradation, ecological risks, and recycling challenges in real-world aquatic environments, while proposing future directions for intelligent material design, mechanistic studies, and environmental safety assessments for engineering applications.

KEYWORDS

Graphene oxide; Water disinfection; Antibacterial mechanism; Biofilm control; Environmental risk

1 Introduction

The study of antibacterial properties of graphene-based nanomaterials and their application potential in water disinfection holds significant theoretical and engineering value. With the worsening global water scarcity and pollution, water disinfection—a critical component for ensuring drinking water safety—faces unprecedented challenges. While traditional chlorine disinfection is cost-effective and widely used, it generates carcinogenic byproducts like trihalomethanes (THMs)and haloacetic acids (HAAs). Ultraviolet disinfection, though producing no such byproducts, demonstrates sensitivity to particulate matter concentrations in water and lacks sustained disinfection capabilities. More critically, the widespread misuse of antibiotics has led to the proliferation of drug-resistant bacteria and resistance genes (ARGs) in aquatic environments, posing a severe threat to global public health. Against this backdrop, developing new, efficient, safe, and sustainable water disinfection technologies has become imperative. As an emerging two-dimensional nanomaterial, graphene-based nanomaterials offer innovative solutions through their unique physicochemical properties. Graphene-based oxides, containing oxygen-containing functional groups (such as hydroxyl and carboxyl groups), enhance hydrophilicity and biocompatibility, making them suitable for water treatment applications. Reduced graphene oxide improves conductivity and rigidity by reducing oxygen content, thereby optimizing antibacterial activity. These characteristics enable graphene-based nanomaterials to form efficient interfaces upon contact with water, effectively promoting pollutant adsorption and microbial inactivation.For example, the unique structure of GO supports a variety of functional modifications, such as the addition of metal nanoparticles or polymers, to improve disinfection capacity [1].Graphene boasts a theoretical specific surface area of 2630 m^2/g [2], providing abundant sites for microbial adsorption. Its exceptional mechanical strength (elastic modulus approximately 1 TPa) enables physical disruption of cell membrane integrity. The tunable electronic properties grant it superior photothermal conversion capabilities and catalytic activity, generating oxidative stress through reactive oxygen species (ROS). This synergistic antimicrobial mechanism effectively reduces the risk of microbial resistance development, offering a crucial direction for developing next-generation efficient and safe water disinfection technologies.

Domestic and international scholars have conducted systematic and in-depth research on the antibacterial properties and applications of graphene-based nanomaterials. Graphene-based nanomaterials directly damage bacterial cell membranes through surface contact. The high flexibility of graphene oxide (GO) allows it to encapsulate bacteria in parallel contact, while the higher rigidity of reduced graphene oxide (rGO) promotes edge cutting in vertical contact, leading to cell membrane rupture and content leakage [3]. For instance, the antibacterial effect of GO against Gram-positive bacteria (such as Staphylococcus aureus) may originate from its encapsulation mechanism. Adding 50 mg/L of wall acid ester can reduce GO's antibacterial activity by 4-5 times, demonstrating the role of wall acid structure in this mechanism [4]. In contrast, vertical graphene coatings achieve 65.60% sterilization rate against Staphylococcus aureus and

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43.89% against Escherichia coli through edge contact in vitro [5], confirming the efficiency of vertical modes. Physical contact is independent of antibiotics, reducing the development of drug resistance [6]. Regarding antibacterial mechanisms, Akhavan and Ghodsi demonstrated through precise control experiments that GO exhibits significant differences in antibacterial efficacy against Gram-positive and Gram-negative bacteria, a phenomenon attributed to variations in their cell wall structures and chemical compositions [7]. Tu et al. [8] for the first time directly observed the process of GO nanosheets physically cutting cell membranes through the "nano-knife" effect by high-resolution microscopy, and used atomic force microscopy to quantitatively analyze the force size, providing intuitive evidence for understanding the physical antibacterial mechanism of graphene-based nanomaterials.

Graphene-based nanomaterials demonstrate exceptional performance in water disinfection applications, particularly in membrane filtration, photocatalysis, and composite systems that effectively neutralize pathogens and remove contaminants. Their application potential stems from three key advantages: high pathogen inactivation efficiency, low energy consumption, and resistance to biofouling. The effectiveness of these systems primarily depends on material design and environmental adaptability. Graphene membranes can create two-dimensional confinement channels that selectively eliminate microorganisms and heavy metals.After optimization, it can maintain high water flux (about 150 L m h) and 99.9% disinfection efficiency [9]. For example, rGO based membrane regulates channels and electrical density [10]. The advantages of these membranes are low surface roughness and high hydrophilicity, which reduce the attachment of dirt.To enhance water and ion retention, Perreault et al [11]. developed graphene oxide (GO)-modified filter membranes. Through precise control of the membrane's surface structure and chemical properties, they achieved a 99.9% removal rate of Escherichia coli while significantly reducing membrane fouling issues. Research indicates that the GO coating not only boosts the membrane's antibacterial performance but also enhances anti-fouling capabilities by improving surface hydrophilicity. In photothermal antimicrobial applications, vertical graphene coatings demonstrate enhanced efficacy under light exposure, with bacterial inactivation achieved through thermal activation via infrared or visible light [5]. Photocatalytic antibacterial effects are equally remarkable: for instance, dual-mode antimicrobial hydrogel (DMAH) combining photothermal and chemical release mechanisms achieves 99.84% eradication of methicillin-resistant Staphylococcus aureus [12]. However, most of these studies remain confined to ideal laboratory settings, falling short of real-world application requirements.The mechanisms by which different water quality parameters (such as pH and ionic strength) affect the stability and antibacterial properties of graphene oxide (GO) remain unclear. Notably, divalent cations like Ca^{2+} and Mg^{2+} can induce GO nanosheet aggregation and sedimentation through charge neutralization, thereby reducing their bioavailability [13]. Furthermore, long-term applications require further evaluation of GO nanosheet release and ecological risks, particularly regarding migration patterns during drinking water treatment processes and potential impacts on aquatic ecosystems, which still demand in-depth research.

Furthermore, existing studies lack systematic comparisons of how structural parameters (such as oxidation levels, layer thickness, and dimensions) affect the antibacterial properties of graphene-based nanomaterials, making it difficult to establish precise correlations. The cost-effectiveness of large-scale production and practical application models in water treatment engineering also require in-depth exploration, particularly regarding the long-term operational stability and regenerative performance of continuous flow reactors. These knowledge gaps severely hinder the practical application of graphene-based nanomaterials in water treatment. There is an urgent need to conduct systematic research on the antibacterial mechanisms and engineering applications of graphene-based nanomaterials, providing new solutions to address current technological bottlenecks in water disinfection.

1.1 The urgency and technical bottlenecks of global water disinfection needs

With the acceleration of global population growth and industrialization, water pollution has become increasingly severe, making the demand for efficient water disinfection technologies particularly urgent. Traditional disinfection methods such as chlorine disinfection produce harmful by-products, while ultraviolet treatment faces technical bottlenecks like high energy consumption and poor sustained effectiveness [14].The current water treatment systems face major challenges including difficulties in completely eliminating drug-resistant bacterial strains, secondary pollution generated during treatment processes, and excessively high operational costs [15]. These technical limitations have driven researchers to seek more efficient and environmentally friendly new disinfection materials.

1.2 Antibacterial characteristics and advantages of graphene-based nanomaterials

Graphene-based nanomaterials exhibit superior antibacterial properties compared to conventional antimicrobial agents due to their unique two-dimensional structure and diverse surface chemical characteristics. Research demonstrates that graphene oxide (GO) demonstrates broad-spectrum antibacterial activity against both Gram-positive and Gram-negative bacteria. Its antimicrobial advantages are primarily manifested in three aspects: 1) Physical fragmentation through sharp edges that damage bacterial cell membranes; 2) Generation of reactive oxygen species

(ROS) during chemical oxidation that induces oxidative stress; and 3) Unique surface adsorption capability for effective microbial capture [16]. Compared to conventional antibiotics, the physical action mechanisms of graphene materials significantly reduce the risk of developing bacterial resistance.

1.3 Application prospects of antibacterial nanomaterials in environmental field

Graphene-based nanomaterials also show multiple application potential in the field of environmental governance. In terms of water treatment, the large specific surface area and rich functional groups of graphene-based nanomaterials can realize both microbial inactivation and pollutant adsorption [17]. In soil remediation, GO can enhance the leaching efficiency of pollutants [18].In the field of food packaging, graphene composites not only extend food shelf life but also reduce environmental pollution caused by traditional plastics [19]. Notably, the composite systems formed by graphene with metal nanoparticles (such as Pd and Ni) exhibit synergistic antibacterial effects, demonstrating exceptional performance in catalytic disinfection.

1.4 Current controversies and challenges in the research

Despite its promising prospects, research on graphene-based antibacterial materials remains fraught with key controversies. The academic community has yet to reach consensus regarding the relative contributions of parallel and vertical interactions in antimicrobial mechanisms. Practical applications face persistent challenges: Complex aquatic environments may induce nanomaterial aggregation and surface passivation; organic adsorption could mask active sites; and prolonged use might lead to diminished antibacterial efficacy [20].Of particular significance are the potential impacts of graphene materials on aquatic microbial communities and alterations in bacterial-phage interactions [21], which demand urgent systematic evaluation of ecological risks. Furthermore, breakthroughs remain necessary in scaling up production cost-effectiveness and developing material recycling technologies.

2 Antibacterial mechanism and structural characteristics of graphene-based nanomaterials

2.1 Physical and chemical antimicrobial mechanisms

Graphene-based nanomaterials exhibit exceptional antibacterial properties due to their unique two-dimensional structure. Studies reveal that the edges of graphene nanomaterials possess atomic-level sharpness, enabling direct penetration of bacterial cell membranes and causing physical damage. This mechanical cutting effect is closely related to the material's rigidity. GO, with its high surface oxygen content, demonstrates good flexibility for bacterial encapsulation; whereas rGO, with reduced oxygen content, exhibits enhanced rigidity and is better suited for edge contact with bacteria. The antibacterial efficacy of vertically aligned graphene coatings was demonstrated against Staphylococcus aureus (65.60%) and Escherichia coli (43.89%), confirming the effectiveness of edge contact [22]. Notably, this physical mechanism is less likely to induce bacterial resistance, offering new strategies for combating drug-resistant pathogens. Graphene-based materials can generate reactive oxygen species (ROS) through multiple pathways, forming the core of their chemical antibacterial mechanism. Research shows that Ni/rGO nanocomposites achieve over 99% inactivation efficiency against Escherichia coli and Bacillus subtilis by regulating oxygen vacancy numbers. Under visible light catalysis, the Zn-TiO/rGO (HTG) system significantly enhances ROS generation, reaching 98% antibacterial efficacy within a short period. Graphene quantum dots (GQDs) produce ROS through photo power and peroxidase activity, but their applications are limited by substrate supply and light conditions [23]. In complex systems, the generation of ROS often produces a synergistic antibacterial effect with the release of metal ions (e. g., Ag^+) and photothermal effects [24]. These chemical oxidation processes can lead to bacterial membrane lipid peroxidation, protein denaturation and DNA damage, and ultimately lead to cell death [25].

2.2 Influence of material morphology on antibacterial efficiency

Graphene-based materials exhibit distinct antibacterial performance characteristics across different morphologies. Graphene oxide (GO) demonstrates extensive applications in antimicrobial fields owing to its high biocompatibility and design flexibility, with effective antibacterial effects achieved through "GO/non-GO" composite strategies [26]. Reduced graphene oxide (rGO) exhibits enhanced photocatalytic antibacterial efficacy due to its improved conductivity and oxygen vacancy formation. Graphene quantum dots (GQDs) demonstrate effective low-concentration antibacterial action through quantum confinement effects and edge-active sites. Studies reveal that the antibacterial efficacy of GO against Gram-positive bacteria can be reduced by 4-5 times when supplemented with exogenous peptidoglycan, indicating a mechanism closely related to bacterial cell wall structure. The antibacterial efficiency differences among material morphologies are determined by parameters including specific surface area, functional group distribution, and electron mobility.

3 Antimicrobial resistance of bacterial species

3.1 Differences in cell wall structure response between Gram-positive and Gram-negative bacteria

Research demonstrates that graphene oxide (GO) exhibits distinct antimicrobial effects against Gram-positive and Gram-negative bacteria. This difference primarily stems from their cell wall structures: Gram-positive bacteria possess a 20-80 nm peptidoglycan layer with abundant negatively charged phospholipidic acid, while Gram-negative bacteria feature a more complex outer membrane composed of lipopolysaccharides and phospholipids. Experimental evidence shows that adding 50 mg/L phospholipidic acid exogenously reduces GO's antibacterial activity against Staphylococcus aureus by 4-5 times, directly confirming its protective role in resisting GO attack in Gram-positive bacteria [27]. In addition, the difference in in vitro inhibition rates of two typical bacterial strains on vertical graphene coating further verified the key influence of cell wall structure on antibacterial effect [5].

3.2 Molecular mechanism of biofilm formation and antibacterial resistance

As a critical defense mechanism for bacteria against environmental stress, biofilm formation involves complex molecular regulatory networks. Nanomaterials can disrupt biofilms through multiple mechanisms including mechanical damage, electron transfer, enzymatic degradation, oxidative stress, and thermal effects. Research demonstrates that graphene-based materials effectively inhibit biofilm corrosion by sulfate-reducing bacteria on copper surfaces. While they cannot prevent initial bacterial attachment, these materials significantly reduce biofilm activity through surface contact sterilization. At the molecular level, bacteria activate antioxidant response systems when exposed to nanomaterial stressors, while simultaneously promoting extracellular polymeric substance (EPS) secretion to enhance biofilm formation [28]. Theoretical prediction of XDLVO shows that the surface characteristics of the material will significantly affect the bacterial adhesion trend, and then regulate the development dynamics of biofilm [29]. The newly proposed nanopore-enhanced electron transport (NBET) mechanism reveals a novel antimicrobial pathway distinct from traditional reactive oxygen species (ROS) mechanisms, which disrupts bacterial electron transfer networks to dismantle biofilms [30]. Furthermore, prolonged sub-lethal exposure to graphene oxide (GO) induces adaptive resistance mechanisms in bacteria, including alterations in biofilm matrix composition and upregulation of antibiotic resistance genes.

4 Synergistic antibacterial system of composite materials

4.1 Interfacial effects of metal nanoparticle composites

The composite system of graphene and metal nanoparticles demonstrates remarkable synergistic antibacterial effects. Studies indicate that atomically dispersed palladium clusters (Pd) loaded onto a nanodiamond-graphene substrate can be fabricated into composite materials with excellent catalytic antibacterial properties [31]. This composite structure significantly enhances the exposure of active sites and catalytic efficiency through the metal-graphene interface effect. The electron transfer between metal nanoparticles and graphene can promote the continuous generation of ROS, while the two-dimensional structure of graphene provides a uniform dispersion carrier platform for metal nanoparticles [32]. In particular, the self-assembly system of copper sulfide nanoparticles (CuS NP) and rGO not only showed enhanced photothermal antibacterial effect, but also promoted vascularized bone integration through the continuous release of copper ions [33].

4.2 Band control strategies for semiconductor photocatalysts

Semiconductor/graphene composite photocatalysts engineered through band engineering demonstrate excellent visible light-responsive antibacterial performance. The zinc-titanium oxide/reduced graphene oxide (Zn-TiO/rGO) composite system (HTGZ) exhibits superhydrophilic properties and good dispersion, achieving over 98% antibacterial efficiency under visible light. This enhancement stems from the heterostructure between graphene and semiconductors, which effectively promotes the separation of photogenerated electron-hole pairs and suppresses recombination. As an electron acceptor, rGO significantly enhances the carrier mobility in the photocatalytic system while its large specific surface area facilitates active site exposure. Precise band structure modulation enables the composite material to maintain high antibacterial activity while also exhibiting tissue repair capabilities [33].

4.3 Optimization of sustained release and recovery performance of hydrogel carriers

The combination of graphene-based composites with biodegradable carriers provides a new approach to solve the recycling problem of nanomaterials. The composite system based on bacterial cellulose has shown potential applications in targeted drug delivery, antibacterial dressings and other fields [34].By incorporating reduced graphene oxide (rGO) with cellulose nanofibers (CNF) in a low eutectic solvent (DES), films exhibiting excellent mechanical properties and recyclability can be fabricated [35]. The hydrogel network architecture not only enables controlled release of antimicrobial components but also provides abundant active sites for microbial adsorption through its three-dimensional porous structure. Laser-aided graphene technology further enhances the functionalization capabilities of the composite materials, allowing selective modification for enzyme immobilization or enhanced electrical conductivity. These carrier systems maintain antibacterial efficacy while significantly improving material recycling efficiency and environmental sustainability.

5 Performance decay and existence risks

5.1 Influence of organic matter adsorption in complex aquatic environment

Graphene-based nanomaterials interact with various organic compounds in aquatic environments. Research indicates that EPS (Exfoliated Cell Walls), which are widely present in water bodies, significantly influence the environmental behavior and risks of graphene oxide (GO). These complex organic components not only alter the dispersion state of GO but may also affect its antibacterial activity through surface adsorption. Notably, GO demonstrates high adsorption capacity for heavy metals like cadmium (Cd), and such combined pollution may exert synergistic toxic effects on aquatic organisms [36].

5.2 Kinetic analysis of material aggregation state change

The aggregation behavior of graphene-based nanomaterials (GFNs) in aquatic environments directly determines the persistence of their antibacterial efficacy. Experimental studies reveal that graphene oxide quantum dots (GOQDs) exhibit superior dispersion compared to graphene under all pH conditions [37]. This dispersion difference results in distinct migration and transformation behaviors of the materials within water systems, ultimately affecting their contact efficiency with microorganisms.Long-term (95 d) presence of GO nanomaterials leads to a reduction in the average particle size by 1 mm and deterioration of sedimentation performance (SVI 74.1 mL/g)[38].

5.3 Surface passivation during long-term use

Graphene materials undergo surface property changes during prolonged use. While graphene atom layers can protect metals like copper from sulfate-reducing bacteria corrosion, they fail to prevent bacterial adhesion and biofilm formation. This surface passivation gradually diminishes the material's antibacterial efficacy. Moreover, during long-term filtration of surface water, the varying microstructures of graphene oxide (GO) membranes lead to different levels of biofilm accumulation and biological fouling [39].

5.4 Detection methods for environmental residues of nanomaterials

To address environmental persistence of graphene-based nanomaterials, researchers have developed multiple detection techniques. Carbon-14 labeled flake graphene (FLG) has been employed to investigate the bioavailability of graphene in benthic organisms [40]. This methodology enables precise tracking of graphene's migration and transformation processes within sediment-water systems.In addition, by analyzing the structural composition and design strategies of graphene-based materials, the residual risk in different environmental media can be evaluated [41].

5.5 Potential impacts on aquatic microbial communities

Graphene materials significantly influence aquatic microbial communities. Research has shown that graphene oxide (GO) promotes filamentous bacterial proliferation and alters microbial community structure. In algal systems, both GO and graphene oxide quantum dots (GOQDs) exhibit acute toxicity effects on Microcystis. Notably, graphene materials also affect bacteriophage-bacteria interactions. For instance, amino-functionalized graphene oxide (AGO) inhibits the growth of Pseudomonas aeruginosa Y12 and reduces phage lysis efficiency.

5.6 Status of development of material recovery and recycling technologies

Currently, recycling and regeneration technologies for graphene-based antibacterial materials remain in the developmental stage. Research indicates that regulating the transport properties of graphene-based composites can enhance their cycling stability. In agriculture, graphene-based nanomaterials are widely used to develop efficient delivery systems for agricultural chemicals due to their high specific surface area, offering new approaches for material recycling. However, achieving large-scale recycling while maintaining the antibacterial properties of the materials remains a major challenge in current research.

6 Summary

Current research indicates that the antibacterial efficacy of graphene-based nanomaterials stems from the synergistic interaction between physical cleavage and chemical oxidation. Physically, the sharp edges of these materials directly disrupt microbial cell membranes through mechanical damage. Chemically, the continuous generation of reactive oxygen species (ROS) induces bacterial oxidative stress. Notably, different morphologies exhibit distinct dominant mechanisms [42]: graphene oxide (GO) shows Gram-positive bacterial susceptibility significantly influenced by phospholipid concentration, while vertically aligned graphene coatings demonstrate 65.6% inherent antibacterial efficiency with photothermal synergy. Future theoretical models should integrate material-microbe interface dynamics, particularly the regulation of surface chemistry by biomolecular adsorption. A key environmental application challenge lies in mitigating performance degradation caused by material aggregation. Recent studies reveal that nickel/reduced graphene oxide (Ni/rGO) achieves 99.5% sterilization efficiency through oxygen vacancy concentration modulation, while nano-diamond-graphene-supported palladium clusters exhibit groundbreaking antibacterial performance as atomically dispersed catalysts. In engineering applications, hydrogel carrier technology extends material lifespan through controlled-release mechanisms, while the cellulose-montmorillonite composite coating achieves integrated antibacterial, barrier, and antioxidant functionalities [43]. Key challenges for large-scale implementation include: developing strategies to suppress organic competition adsorption in complex aquatic environments; constructing rapid ion transport networks based on vertical conductive channels; and creating surface regeneration technologies for recyclable materials.

Critical challenges in this field include: cross-scale analysis of bacterial compensatory resistance mechanisms, which suggests integrating single-cell Raman spectroscopy with transcriptomics; precise tracking technologies for material-environment interactions, drawing inspiration from carbon isotope-labeled nanoparticle tracing methods; and multi-trophic-level ecological safety assessments requiring standardized aquatic microcosm testing systems. In material design, priority should be given to developing: dynamically responsive intelligent antibacterial composites; defect repair techniques using biomimetic interface modifications; and rapid antimicrobial efficacy monitoring systems based on field-effect transistors (FET). The integration of theoretical simulations and high-throughput experiments will accelerate the application of "materials genome" principles in antibacterial nanotechnology.

References

[1] ANICHINI C, SAMORì P. Graphene-Based Hybrid Functional Materials [J]. Small, 2021, 17(33): e2100514.

[2] GEIM A K, NOVOSELOV K S. The rise of graphene [J]. Nature Materials, 2007, 6(3): 183-91.

[3] GUO Z, ZHANG P, XIE C, et al. Defining the Surface Oxygen Threshold That Switches the Interaction Mode of Graphene Oxide with Bacteria [J]. ACS Nano, 2023, 17(7): 6350-61.

[4] WANG M, LI Z, ZHANG Y, et al. Interaction with teichoic acids contributes to highly effective antibacterial activity of graphene oxide on Gram-positive bacteria [J]. J Hazard Mater, 2021, 412125333.

[5] XING M, QIAN W, YE K, et al. All-in-one design of titanium-based dental implant systems for enhanced soft and hard tissue integration [J]. Biomaterials, 2025, 320123251.

[6] AZIZI-LALABADI M, HASHEMI H, FENG J, et al. Carbon nanomaterials against pathogens; the antimicrobial activity of carbon nanotubes, graphene/graphene oxide, fullerenes, and their nanocomposites [J]. Adv Colloid Interface Sci, 2020, 284102250.

[7] AKHAVAN O, GHADERI E. Toxicity of Graphene and Graphene Oxide Nanowalls Against Bacteria [J]. ACS Nano, 2010, 4(10): 5731-6.

[8] TU Y, LV M, XIU P, et al. Destructive extraction of phospholipids from Escherichia coli membranes by graphene nanosheets [J]. Nature Nanotechnology, 2013, 8(8): 594-601.

[9] YU R, WANG H, WANG R, et al. Polyphenol modified natural collagen fibrous network towards sustainable and antibacterial microfiltration membrane for efficient water disinfection [J]. Water Res, 2022, 218118469.

[10] XING J, ZHANG H, WEI G, et al. Improving the Performance of the Lamellar Reduced Graphene Oxide/Molybdenum Sulfide Nanofiltration Membrane through Accelerated Water-Transport Channels and Capacitively Enhanced Charge Density [J]. Environ Sci Technol, 2023, 57(1): 615-25.

[11] PERREAULT F, DE FARIA A F, NEJATI S, et al. Antimicrobial Properties of Graphene Oxide Nanosheets: Why Size Matters [J]. ACS Nano, 2015, 9 (7): 7226-36.

[12] GONG C, GUAN W, LIU X, et al. Biomimetic Bacteriophage-Like Particles Formed from Probiotic Extracts and NO Donors for Eradicating

Multidrug-Resistant Staphylococcus aureus [J]. Adv Mater, 2022, 34(45): e2206134.
[13] AHMED F, RODRIGUES D F. Investigation of acute effects of graphene oxide on wastewater microbial community: A case study [J]. Journal of Hazardous Materials, 2013, 256-25733-9.
[14] LI Y, ZHANG K, YIN Y, et al. Amino-functionalized graphene oxide affects bacteria – phage interactions in aquatic environments [J]. Water Research, 2024, 259121840.
[15] SHAHROUDI S, PARVINNASAB A, SALAHINEJAD E, et al. Efficacy of 3D-printed chitosan-cerium oxide dressings coated with vancomycin-loaded alginate for chronic wounds management [J]. Carbohydrate Polymers, 2025, 349123036.
[16] WANG J, ZHANG J, HAN L, et al. Graphene-based materials for adsorptive removal of pollutants from water and underlying interaction mechanism [J]. Advances in Colloid and Interface Science, 2021, 289102360.
[17] KONG Q, SHI X, MA W, et al. Strategies to improve the adsorption properties of graphene-based adsorbent towards heavy metal ions and their compound pollutants: A review [J]. Journal of Hazardous Materials, 2021, 415125690.
[18] BERYANI A, BIANCO C, CASASSO A, et al. Exploring the potential of graphene oxide nanosheets for porous media decontamination from cationic dyes [J]. Journal of Hazardous Materials, 2022, 424127468.
[19] ALIZADEH SANI M, KHEZERLOU A, REZVANI-GHALHARI M, et al. Advanced carbon-based nanomaterials: Application in the development of multifunctional next-generation food packaging materials [J]. Advances in Colloid and Interface Science, 2025, 339103422.
[20] ZHANG Q, ZHANG C. Chronic Exposure to Low Concentration of Graphene Oxide Increases Bacterial Pathogenicity via the Envelope Stress Response [J]. Environmental Science & Technology, 2020, 54(19): 12412-22.
[21] YIN M, WU J, DENG M, et al. Multifunctional Magnesium Organic Framework-Based Microneedle Patch for Accelerating Diabetic Wound Healing [J]. ACS Nano, 2021, 15(11): 17842-53.
[22] LI B, MAO J, WU J, et al. Nano–Bio Interactions: Biofilm-Targeted Antibacterial Nanomaterials [J]. Small, 2024, 20(7): 2306135.
[23] WU W, QIN Y, FANG Y, et al. Based on multi-omics technology study the antibacterial mechanisms of pH-dependent N-GQDs beyond ROS [J]. Journal of Hazardous Materials, 2023, 441129954.
[24] CHILKOOR G, SHRESTHA N, KUTANA A, et al. Atomic Layers of Graphene for Microbial Corrosion Prevention [J]. ACS Nano, 2021, 15(1): 447-54.
[25] GENERALOVA A N, DUSHINA A O. Metal/metal oxide nanoparticles with antibacterial activity and their potential to disrupt bacterial biofilms: Recent advances with emphasis on the underlying mechanisms [J]. Advances in Colloid and Interface Science, 2025, 345103626.
[26] ROSŁOŃ I E, JAPARIDZE A, STEENEKEN P G, et al. Probing nanomotion of single bacteria with graphene drums [J]. Nature Nanotechnology, 2022, 17(6): 637-42.
[27] SEIDI F, ARABI SHAMSABADI A, DADASHI FIROUZJAEI M, et al. MXenes Antibacterial Properties and Applications: A Review and Perspective [J]. Small, 2023, 19(14): 2206716.
[28] ZHENG S, LI J, YAN W, et al. Biofilm formation and antioxidation were responsible for the increased resistance of N. eutropha to chloramination for drinking water treatment [J]. Water Research, 2024, 254121432.
[29] JING X, WU Y, WANG D, et al. Ionic Strength-Dependent Attachment of Pseudomonas aeruginosa PAO1 on Graphene Oxide Surfaces [J]. Environmental Science & Technology, 2022, 56(23): 16707-15.
[30] SHI T, HOU X, GUO S, et al. Nanohole-boosted electron transport between nanomaterials and bacteria as a concept for nano–bio interactions [J]. Nature Communications, 2021, 12(1): 493.
[31] CUI F, LI T, WANG D, et al. Recent advances in carbon-based nanomaterials for combating bacterial biofilm-associated infections [J]. Journal of Hazardous Materials, 2022, 431128597.
[32] YANG Y, LI M, ZHOU B, et al. Graphene oxide/gallium nanoderivative as a multifunctional modulator of osteoblastogenesis and osteoclastogenesis for the synergistic therapy of implant-related bone infection [J]. Bioactive Materials, 2023, 25(594-614.
[33] ZHANG Z, WANG Y, TENG W, et al. An orthobiologics-free strategy for synergistic photocatalytic antibacterial and osseointegration [J]. Biomaterials, 2021, 274120853.
[34] LIU Y, LIU H, GUO S, et al. A review of carbon nanomaterials/bacterial cellulose composites for nanomedicine applications [J]. Carbohydrate Polymers, 2024, 323121445.
[35] LIU Q, SUN W, YUAN T, et al. Green and cost-effective synthesis of flexible, highly conductive cellulose nanofiber/reduced graphene oxide composite film with deep eutectic solvent [J]. Carbohydrate Polymers, 2021, 272118514.
[36] WU K, LI Y, ZHOU Q, et al. Integrating FTIR 2D correlation analyses, regular and omics analyses studies on the interaction and algal toxicity mechanisms between graphene oxide and cadmium [J]. Journal of Hazardous Materials, 2023, 443130298.
[37] YAN Z, YANG X, LYNCH I, et al. Comparative evaluation of the mechanisms of toxicity of graphene oxide and graphene oxide quantum dots to blue-green algae Microcystis aeruginosa in the aquatic environment [J]. Journal of Hazardous Materials, 2022, 425127898.
[38] ABU ELELLA M H, GODA E S, ABDALLAH H M, et al. Green engineering of TMC-CMS nanoparticles decorated graphene sheets for targeting M. tuberculosis [J]. Carbohydrate Polymers, 2023, 303120443.
[39] HAMEED S, SHARIF S, OVAIS M, et al. Emerging trends and future challenges of advanced 2D nanomaterials for combating bacterial resistance [J]. Bioactive Materials, 2024, 38(225-57.
[40] LU K, ZHA Y, DONG S, et al. Uptake Route Altered the Bioavailability of Graphene in Misgurnus anguillicaudatus: Comparing Waterborne and Sediment Exposures [J]. Environmental Science & Technology, 2022, 56(13): 9435-45.
[41] DING G, LI H, ZHAO J, et al. Nanomaterials for Flexible Neuromorphics [J]. Chemical Reviews, 2024, 124(22): 12738-843.
[42] LU K, HU Q, ZHAI L, et al. Mineralization of Few-Layer Graphene Made It Bioavailable in Chlamydomonas reinhardtii [J]. Environmental Science & Technology, 2023, 57(40): 15255-65.
[43] CUI Y, CHENG Y, XU Z, et al. Cellulose-Based Transparent Edible Antibacterial Oxygen-Barrier Coating for Long-Term Fruit Preservation [J]. Advanced Science, 2024, 11(48): 2409560.