The Antibacterial Applications of Graphene and Its Derivatives

Lin Shi, Jiongrun Chen, Lijing Teng, Lin Wang, Guanglin Zhu, Sa Liu, Zhengtang Luo, Xuetao Shi,* Yingjun Wang, and Li Ren*

Graphene materials have unique structures and outstanding thermal, optical, mechanical and electronic properties. In the last decade, these materials have attracted substantial interest in the field of nanomaterials, with applications ranging from biosensors to biomedicine. Among these applications, great advances have been made in the field of antibacterial agents. Here, recent advancements in the use of graphene and its derivatives as antibacterial agents are reviewed. Graphene is used in three forms: the pristine form; mixed with other antibacterial agents, such as Ag and chitosan; or with a base material, such as poly (N-vinylcarbazole) (PVK) and poly (lactic acid) (PLA). The main mechanisms proposed to explain the antibacterial behaviors of graphene and its derivatives are the membrane stress hypothesis, the oxidative stress hypothesis, the entrapment hypothesis, the electron transfer hypothesis and the photothermal hypothesis. This review describes contributions to improving these promising materials for antibacterial applications.
1. Introduction

Antibacterial materials are increasingly essential in daily life to effectively protect human health from different forms of pollutants, including organic, inorganic and biological substances.[1] Additionally, bacterial infections can lead to implant failure, which may cause major economic losses and suffering among patients. Despite the use of preoperative antibiotic prophylaxis and the aseptic processing of materials, bacterial infections continue to cause approximately 4% to 6% of implant failures during the early implantation period. Therefore, novel antibacterial agents are urgently needed for both daily and medical uses. Antibacterial materials include antibiotics,[2] metal ions/oxides,[3] antimicrobial peptides (AMPs),[4] and quaternary ammonium compounds.[5] Antibiotics are rapid and effective antimicrobial agents, but bacterial resistance caused by the abuse of antibiotics is a serious problem in the medical field.[6] Metal ions/oxides have long been used as sterilization agents in different forms and have broad-spectrum antimicrobial properties against bacterial, fungal, and viral agents.[7,8] However, this type of antibacterial agent is toxic to some types of mammalian cells.[9] The cost of extracting pure AMPs as new antibacterial agents is high, limiting the extensive use of AMPs despite their immunomodulatory properties, abundance and broad-spectrum antimicrobial activities.[10,11] Similar to antibiotics, quaternary ammonium compounds can induce drug resistance after long-term use, although they are efficient and convenient. Compared with these antimicrobial agents, graphene and its derivatives possess relatively high bacterial toxicity, negligible mammalian cytotoxicity and other favorable properties, attracting considerable interest in the field of antibacterial materials.[12]

Since the 1980s, nanomaterials and nanotechnology have undergone major development, with nanocarbon materials becoming a novel field of research. With the ability to form various covalent bonds (sp, sp², sp³) between atoms, carbon has different crystal structures with distinct physical and chemical properties, including diamond, graphite, fullerene, and carbon nanotubes.[13] Geim and Novoselov enriched this list by isolating graphene from graphite in 2004, for which they received the 2010 Nobel Prize in physics.[14] Graphene (Figure 1), a single-atom-thick sheet composed of sp²-hybridized carbon atoms, has attracted substantial attention due to its excellent physicochemical properties.[15] Graphene has a high specific surface area, exceptional electronic mobility and outstanding mechanical strength.[16,17] Graphene and its derivatives materials have extraordinary potential for numerous applications, including biological applications. Many studies have investigated the use of graphene and its derivatives materials as molecular sieving membranes,[18] biosensors,[19] drug delivery systems,[20] fluorescence imaging probes[21] and tissue engineering scaffolds.[22] Among these applications, researchers have specifically focused on the antibacterial applications of graphene, its derivatives and composite materials.[23]

Graphene oxide (GO) and other graphene derivatives have been impregnated into paper and cotton fabrics for practical applications and exhibit antibacterial activity against common dental pathogens, for example, illustrating their promise in the biomedical field.[5,24,25] Because of their relatively high specific surface areas, abundant reactive surface functionalities, excellent physical properties and water solubility, graphene and its derivatives appear to have the potential to serve as nanoscale building blocks for composite antibacterial materials.[26] Moreover, the strong van der Waals forces between graphene and graphene derivative nanosheets facilitate aggregation, and inserting molecules such as poly(sodium 4-styrenesulfonate) or nanoparticles (NPs) is an effective approach to prevent restacking and enhance their bactericidal performance.[27,28] With outstanding mechanical strength, graphene and its derivatives are also used as nanofiller to improve the mechanical properties of composite antibacterial materials.[29]

Although the antibacterial properties of graphene and its derivatives are impressive, mechanistic studies examining how these materials antagonize bacteria have yielded conflicting or confusing results. Herein, we attempt to summarize recent progress in the use of graphene, its derivatives and composite materials for antibacterial applications. Firstly, we introduce the antibacterial activity of graphene and its derivatives and the mechanism of this activity, including some contradictory opinions. After that, the synergistic effects of graphene or graphene derivatives with Ag composite materials prepared using different synthesis procedures are described with examples. In the final section, we discuss the compounding of graphene derivatives with other materials, such as ZnO and chitosan, to improve their sterilization capabilities. Although we have made a sincere effort to provide a comprehensive overview, some important new works might not be included due to the rapid development of this field.

2. Antibacterial Activities of Single-Component Graphene and Its Derivatives

Scientists are continuously working to identify materials with comparable or better antibacterial activity than current technologies that are also environmentally friendly and cost effective. The materials of the graphene family, which mainly

National Engineering Research Center for Tissue Restoration and Reconstruction
South China University of Technology
Guangzhou 510006, PR China
E-mail: shxt@scut.edu.cn; psliren@scut.edu.cn

School of Materials Science and Engineering
South China University of Technology
Guangzhou 510640, PR China

Z. Luo
Department of Chemical and Biomolecular Engineering
The Hong Kong University of Science and Technology
Hong Kong 999077, PR China

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include graphene, GO and reduced GO (rGO), appear to fit this description. Because of its abundant functional groups and dispersibility in aqueous media, GO is more widely used.[30]

2.1. The Antibacterial Mechanisms and Activities of Graphene

A variety of mechanisms for the antibacterial activity of graphene materials have been proposed, including membrane stress, oxidative stress and electron transfer.[31] (1) Membrane stress: Nanosheets of graphene can cause physical damage to bacterial membranes. The dynamic degradation of Escherichia coli (E. coli) cell membranes caused by graphene was confirmed with TEM. In computer simulations, graphene can cut and insert itself into cell membranes and extract phospholipids, resulting in a loss of bacterial viability loss. The strong interaction between membrane lipids and graphene is based on the 2D nanostructure with the sp² graphene carbon molecules. Graphene at a higher concentration and larger lateral size should increase bacterial membranes destruction.[32] The same insertion and lipid extraction effects of vacuum-filtered graphene were also observed against Pseudomonas aeruginosa and Staphylococcus aureus (S. aureus).[33] (2) Oxidative stress: Reactive oxygen species (ROS) produced by graphene are harmful to lipids and proteins of bacteria. After the deactivation of lipids and proteins, bacteria can no longer proliferate. According to researchers, this is one of the major mechanisms of graphene toxicity.[34] (3) Electron transfer: Antibacterial activity may be produced via the transfer of electrons from the microbial membrane to the graphene surface rather than stemming from ROS-mediated damage.[35] The electron transfer mechanism was not supported when the chemical vapor deposition (CVD) method was used to prepare large surfaces of graphene films with two types of conductive substrates, Cu and Au.[36] However, without a non-conductive experimental group as a control, the antibacterial activity was positively related to Cu concentration rather than to electron transfer. Li et al. prepared monolayer graphene films on insulator SiO₂, semiconductor Ge and conductor Cu using atmospheric pressure chemical vapor deposition (APCVD).[37] Graphene could act as electron acceptor and attracted electrons away from the bacterial membrane, resulting in compromised membrane integrity.[38] Thus, the graphene-SiO₂ material exhibited neither electron transfer nor antibacterial activity because SiO₂ cannot transfer electrons. However, without a control experimental group for comparison, the toxicity of Cu and Ge ions cannot be excluded in the possible mechanism of the antibacterial activity.

2.2. The Antibacterial Mechanisms and Activities of GO

Oxidative stress, membrane stress, entrapment, the photothermal effect and the basal plane account for the antibacterial effects of GO, GO reduces the viability of common Gram-negative bacteria (E. coli and Salmonella typhimurium), Gram-positive bacteria (Enterococcus faecalis and Bacillus subtilis) and pathogenic bacterial (Klebsiella, Staphylococcus, Pseudomonas syringae and Xanthomonas campestris pv. undulosa), as well as fungal pathogens (Fusarium graminearum and Fusarium oxysporum).[38–40] (1) Oxidative stress: ROS produced by GO suspension damage cellular components, such as lipids and proteins. After being internalized by cells, ROS cause mitochondrial dysfunction and DNA damage.[41,42] By using a specially prepared GO coated atomic force microscopy (AFM) probe, researchers determined that the main interaction force between GO and the E. coli membrane is repulsive rather than adhesive. Therefore, non-contact damage caused by ROS might explain the observed antibacterial properties.[43] (2) Membrane stress: Extremely sharp edges of GO nanosheets may cause physical damage to bacterial membranes and leakage of the intracellular matrix, ultimately leading to inactivation of bacteria.[44,45] Compared with rGO, GO with abundant oxygenous groups is well.
dispersed in bacterial suspension, providing more opportunities to contact with *Ralstonia solanacearum* and generate cell membrane damage with sharp edges.\[^{46}\] Hydrazine was used to reduce GO and synthesize rGO. The antibacterial activity against *E. coli* in a cell viability assay was ranked GO > rGO > graphite (Gt) > graphite oxide (GtO) and was attributed to both membrane and oxidative stress, which are related to state of aggregation and surface functional groups.\[^{47}\]

(3) Entrapment: When trapped in aggregated GO sheets, bacteria are segregated from their environment and unable to proliferate due to blocked iron/gas exchange.\[^{41,48}\] However, the entrapment effect is bacteriostatic rather than bactericidal. Once GO sheets are removed by sonication or other methods, bacteria are able to proliferate if they were not permanently damaged by near-infrared radiation (NIR) when trapped.\[^{49}\]

(4) Photothermal: GO may be used as a photo-absorbing agent for photothermal therapy (PTT) to generate heat from NIR or other laser energy. The synergistic effects of GO and laser energy greatly enhances antibacterial activity.\[^{50,51}\]

(5) The basal plane: The antibacterial activity of GO sheets showed dependence on their lateral dimension in *E. coli* suspensions (Figure 2). Because the aggregation state and oxidation capacity of the sheets were identical, differences in antibacterial activity were exclusively attributed to size. Larger GO nanosheets, which can easily cover cells to prevent proliferation, appear to have stronger antibacterial effects.\[^{52}\] By contrast, some results indicate that smaller GO sheets have higher oxidative and antibacterial capacity.\[^{53}\] These different results emphasize the importance for accurate assessments of antibacterial mechanisms. Another well-designed study supports the notion of the GO basal plane as a functional mechanism. After masking the GO surface with tryptophan and bovine serum albumin (BSA) to prevent the noncovalent adsorption of bacteria, the masked nanosheets killed bacteria less efficiently, indicating that the GO basal plane determines its antibacterial activity.\[^{54}\] Because this experiment was performed in solution, the adsorbate may have decreased the sharpness and flexibility of the GO nanosheets, making it more difficult to damage bacterial membrane or trap the bacteria. To exclude the potential influence of the factors noted above, Advincula et al. prepared flat, large GO films on PET using Langmuir-Blodgett (LB) deposition and observed that the antibacterial activity was layer and surface dependent rather than edge dependent (Figure 3a–c). The bactericidal efficacy of the GO-LB films increased as the number of film layers increased, and several different modes of bacterial inactivation might occur on the basal plane.\[^{55}\]

In addition to direct antibacterial effects, GO can kill bacteria indirectly by selectively promoting the growth of nonpathogenic bacteria. Gut flora are important for human metabolism processes. GO can be used as a membrane scaffold for one of the gut bacterium *Bifidobacterium adolescentis* (*B. adolescentis*) to adhere to and proliferate. After cultivation in the GO suspension, the antagonistic activity of *B. adolescentis* against two gut pathogens, *S. aureus* and *E. coli*, was enhanced.\[^{57}\]

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**Figure 1.** Image and structure of graphene: a) Atomic force microscopy (AFM) image revealing that the folded graphene step is nearly 0.4 nm thick and the substrate graphene step is less than 1 nm thick. b) Transmission electron microscopy (TEM) image of a graphene film obtained by etching of the underlying substrate. c) A few graphene nanosheets at a specific thickness of oxide enhanced with optical contrast by an interference effect. d) Three common types of sp²-nanocarbons: fullerene, carbon nanotubes and graphene. a) Reproduced with permission.\[^{14}\] Copyright 2007, Nature Publishing Group; b) Reproduced with permission.\[^{14}\] Copyright 2007, Nature Publishing Group; c) Reproduced with permission.\[^{14}\] Copyright 2006, American Association for the Advancement of Science; d) Reproduced with permission.\[^{15}\] Copyright 2011, Elsevier Besloten Vennootschap.
2.3. The Antibacterial Mechanisms and Activities of rGO

rGO nanosheets are typically prepared by reducing GO with a reducer, such as hydrazine,[44] dithiothreitol (DTT)[58] or beta mercaptoethanol (BME).[59] Other than these chemical agents, bacteria themselves can also reduce GO through the metabolic activity of glycolysis in a self-limiting manner.[60] Richer in structural defects and carboxyl groups, the edges of rGO nanosheets are more likely to attract and interact with bacteria.[61]

Similar to graphene and GO, the antibacterial mechanisms of rGO mainly include membrane stress and oxidative stress. The antifungal activity of rGO was investigated against three types of fungi that are detrimental to food storage: *Aspergillus oryzae*, *Aspergillus niger* and *F. oxysporum*. Antifungal effectiveness was assessed by determining the half-maximal inhibitory concentrations (IC50), which were 100, 100 and 50 µg mL−1 against *A. oryzae*, *A. niger* and *F. oxysporum*, respectively, relatively low values.[62] Both GO and rGO induced ROS production, but GO generated more ROS, resulting in superior bactericidal activity. In addition, the antibacterial activities of GO and rGO were time and concentration dependent.[58] Gt, GtO, GO and rGO have also been assessed in a turbidity assay against *P. aeruginosa*. The high antibacterial activities of GO and rGO have been attributed to membrane stress caused by sharp nanosheets and DNA fragmentation caused by the relatively high release of ROS.[59] The antibacterial effect of bacterial-reduced GO (BRGO) was mainly due to the detaching of already adherent *E. coli*, accompanied by a slight bactericidal effect.[60]

2.4. The Antibacterial Mechanisms and Activities of Graphene Quantum Dots (GQDs)

A new type of carbon nanoparticle, water-soluble GQDs, has been electrochemically produced by graphite electrolysis and hydrazine reduction at room temperature.[63] Photoexcited GQDs produced a substantial quantity of ROS, reducing the viability of two strains of pathogenic bacteria (*E. coli* and *S. aureus*). By contrast, neither GQDs nor light exposure...
alone induced oxidative stress or antibacterial activity.\cite{64} It was reported that the antibacterial property of GQDs was related to source material and bacterial shape, rather than to photoexcitation. Researchers demonstrated that, GQDs prepared by rupturing C$_{60}$ (C$_{60}$-GQDs) killed more S. aureus than GQDs prepared from GO nanosheets (GO-GQDs). GQDs seem to disrupt the envelopment of (and finally kill) cocci more readily than bacilli such as B. subtilis, E. coli, and P. aeruginosa.\cite{65}

2.5. Contradictory Results for the Antibacterial Activities of Graphene and its Derivatives

The studies described above indicate that graphene and its derivatives are promising antibacterial materials. However, opposing results (no antibacterial activity) for graphene and its derivatives have been presented in other studies.\cite{66} CVD is a common process for preparing large-area graphene films.\cite{37,67} But after being fixed onto substrates, graphene nanosheets lost the nanosize effect and were unable to lacerate or trap bacteria and exhibited no antibacterial activity. A bilayer of graphene shells synthesized through methane pyrolysis was nontoxic to \textit{E. coli} because it did not disperse well in polar solvent.\cite{68} Kellici et al. reported that rGO prepared via a hydrothermal flow method exhibited excellent bactericidal properties, whereas GO obtained by exfoliating graphite oxide did not kill \textit{E. coli} in the same test.\cite{69} Some researchers observed no adverse effect of rGO (synthesized from GO via chemical reduction) on the growth of \textit{E. coli}, even at a relatively high concentration of 100 µg mL$^{-1}$.\cite{70} The Hummer method is a typical and widely used process for preparing GO nanosheets.\cite{71} When anchored with AgNPs, GO-Ag composites exhibited remarkable antibacterial activity against \textit{E. coli}, but GO alone exhibited negligible antibacterial activity. In other words, GO
nanosheets can act as a stabilizer for AgNPs rather than as an antibacterial agent in the bacterial viability assay.[72] An assessment of GO against another Gram-negative bacteria, *P. aeruginosa*, also arrived at the same conclusion.[73] As a result of different bacterial membrane composition, GO nanosheets might be more effective against Gram-positive bacteria than Gram-negative bacteria.[71,74] Furthermore, GO might have neither bacteriostatic nor cytotoxic properties against bacterial and mammalian cells but instead might enhance bacterial growth by increasing cell attachment and proliferation.[75]

These conflicting findings suggest that the physicochemical properties of graphene and its derivatives, such as size, layers and membrane stress, and the interaction between the material and the bacterial cells, which depends on species and concentration, have a strong effect on antibacterial activity.[68] Because many methods (CVD, plasma etching,[70] molecular assembly,[77] liquid-phase exfoliation,[78] Brodie/Hummers methods,[79] and others) are used to prepare graphene and its derivatives, the physicochemical parameters of the prepared materials can vary significantly, leading to different antibacterial performance under the same experimental condition. Additional studies on the detailed interactions between graphene/graphene derivatives and bacteria are urgently needed to make further practical use of these unique materials.

### 3. Antibacterial Activity of Composite Materials Based on Graphene and Its Derivatives

Motivated by the desire to identify a synergistic combination of materials, numerous studies have attempted to synthesize graphene derivative-based antibacterial hybrids. The resulting products have promising applications in water purification, wound dressing, food packaging and other fields.[80]

#### 3.1. Antibacterial Activity of Graphene or Graphene Derivatives Combined with Ag Composite Materials

Ag ions have long been used as an antibacterial agent because of the broad-spectrum activity of Ag and its low propensity to induce microbial resistance. The morphology, particle size and degree of dispersion affect the antibacterial properties and biocompatibility of AgNPs.[73,81–83] Attaching Ag onto the surface of a nanomaterial is an efficient and reliable means of decreasing the size and preventing the aggregation of AgNPs.[84–86] The antibacterial activity of AgNPs is retained after fixation onto the nanosheets of graphene and its derivatives.[87] Moreover, these nanosheets can damage the outer and inner membranes of bacteria and promote an interaction between bacteria and AgNPs.[88,89] The ROS stress, entrapment effects and photothermal effects produced by graphene and its derivatives also contribute to the antibacterial performance of the composites.[90–92]

#### 3.1.1. Graphene/Ag Composite Materials

Both pristine graphene and modified graphene are used as AgNP carriers in antibacterial materials. The use of high-quality graphene as the substrate and sodium dodecyl sulfate (SDS) as the reducing agent yielded well-dispersed AgNPs on the surface of graphene nanosheets. The composite material effectively inhibited the growth and proliferation of *E. coli* (Figure 4a–e).[93] After forming a porous hydrogel structure in the presence of crosslinking agents, the antibacterial graphene/AgNPs composite has great potential for wound dressing.[94,95] Combining other particles with an Ag/graphene composite is a good practice to reduce Ag dosage and introduce additional properties. The electro conductivity of GO was harnessed to prepare “pizza-like” TiO$_2$/Ag$_2$PO$_4$/graphene composites using an iron exchange and hydrothermal method. Ag has an intrinsic bacterial inactivation property, whereas TiO$_2$ can act as photocatalyst to degrade organic dye.[96] Modified graphene nanosheets are also widely used to carry AgNPs, which were generated in situ on the surface of graphene-grafted poly(acrylic acid) (PAA) without additional reductant or complicated treatment.[97]

Although remarkable results have been obtained, the mechanism of the antibacterial effect of graphene derivatives and AgNPs hybrids remains uncertain. To elucidate this mechanism, Shi et al. used two-dimensional electrophoresis and matrix assisted laser desorption ionization (MALDI)–time of flight (TOF)/TOF analysis to estimate the protein expression profiles of *P. aeruginosa* after exposure to graphene-AgNPs and determined that the hybrids produced bacterial toxicity by changing protein expression.[99]

#### 3.1.2. GO/Ag Composite Materials

Direct mixing, in situ reduction and other common material synthesis methods, such as microwave irradiation or plasma modification, are used to prepare GO-Ag composite materials. AgNO$_3$ solution is typically used to synthesize AgNPs with a reducing agent, such as glucose and thiols.[100,101] Mixed GO, AgNO$_3$ and reductant sodium salt in DI water can produce a GO–Ag nanocomposites. The reduction of Ag appears to occur preferentially on the defective points of the GO surface, forming an Ag crystal nucleus, and AgNPs grow at these sites.[102,103] Small and uniform AgNPs form on the large surface area of a GO substrate. In addition to preventing the aggregation of Ag, GO can slow down the AgNPs oxidation process as well, resulting in a long-term bactericidal effect.[104,105] Hydroquinone (HQ), gelatin and sodium borohydride (NaBH$_4$) have also been used as reductants. Ag$^+$ can be absorbed by HQ and reduced in situ in a citrate buffer solution. Paper-like AgNP/GO composite materials exhibited strong antibacterial activity against both *E. coli* and *S. aureus*.[106] Ag nanoprisms were first capped by the gelatin reductant, but the capping ability of the gelatin amino group was lost to the carboxyl group at the edge of GO upon the introduction of GO. Consequently, Ag nanoprisms formed on the wrinkle of GO nanosheets.[107] Similar to GO, AgNO$_3$ can be reduced via a biogenic approach using...
eukaryotic microorganisms or fungi to form AgNPs. F. oxysporum can reduce AgNO₃ and generate Bio-AgNPs. The final Bio-GO-Ag product, consisting of a single layer of GO and Bio-AgNPs, displayed extremely strong biocidal ability against S. typhimurium, even at concentrations as low as 2.0 µg mL⁻¹. Highly monodispersed AgNPs have been anchored using an easy two-phase process involving toluene and water onto GO sheets at the interface of the two phases. Compared with normal AgNPs and GO sheets, monodispersed AgNPs on GO sheets exhibited remarkably enhanced antibacterial activity. Microwave irradiation and dry plasma are rapid and simple methods to prepare Ag-GO nanocomposites. These methods contributed to the formation of narrow size-distributed NPs through rapid nucleation and crystallization.

To prepare water-soluble, less cytotoxic and more stable Ag-GO nanocomposites, some researchers modified GO nanosheets during pretreatment phases. Molecules such as poly(diallyldimethylammonium chloride) (PDDA) have been used to promote the adsorption of prepared AgNPs on GO by electrostatic interactions. DsDNA on the surface of GO sheets can direct the growth of AgNPs and increase the water solubility of the composite. Other molecules, such as...
as polyethyleneimine (PEI), improved the stability or cytocompatibility of the substrate, although a reductant was still needed.[118] Molecules like polydopamine (PDA) are versatile and act not only as a stabilizer or protectant but also as a reducing agent.[119,120] In addition to solvent and substrate, the pH value contributes to NP morphology. A hydrophilic TETA-functioning GO was synthesized to serve as a substrate, stabilizer and reducing agent for AgNPs production. Changing the pH value of the medium by adding NaOH solution affected the particle size and morphology of the NPs. The highest cytotoxicity against E. coli was observed when the distribution of AgNPs was much more narrow at a pH of 11.4.[121] For practical applications, AgNPs and GO were embedded in regenerated nanocomposite cellulose membranes. Compared with membranes containing AgNPs alone, the porous AgGO cellulose membranes provided more opportunities for bacteria to interact with AgNPs.[122] GO-Ag nanocomposites with the ability to inhibit bacterial growth were used to prevent the formation of biofilms on stainless steel surfaces or thin film composites.[123,124]

GO sheets with AgNPs have also been used in electrospun nanofiber mats. GO-Ag was added to the surface of poly (lactide-co-glycolide) (PLGA)-chitosan electrospun mats through covalent bonding by cross-linking 1-ethyl-3-(3’-dimethylaminopropyl) carbodiimide (EDC) and N-hydroxysuccinimide (NHS) to obtain an antibacterial, scalable, and biodegradable coating material.[125] Ternary composite materials consisting of Ag, GO and a third component are useful for water purification.[126] Hybrids with a photocatalyst such as P25 presented photocatalytic degradation of organic dye as well as bacteria.[127,128] To promote recycling and reduce costs, iron-oxide nanoparticles (IONPs) were creatively added to the GO-Ag nanocomposite. GO can absorb NIR and has a photothermal killing effect on bacteria. The magnetic IONPs facilitated the aggregation of materials upon exposure to an external magnetic field (Figure 5). AgNPs are effective antibacterial agents, and with their synergistic function, these nanocomposite materials exhibited remarkable bactericidal activity at a low concentration.[129] Using gold nanoparticles as nucleation seeds during the growth of Ag using an electron-less chemical deposition, Tong et al. obtained Au-Ag core–shell nanoparticles on GO sheets coated with BSA, which decreased the cytotoxicity of GO and increased the attachment of gold nanoparticles.[130]

The synergistic effects of GO and AgNPs cause the bactericidal properties of GO-Ag composite materials. AgNPs can interact with proteins on cell walls and then damage cell membranes, increasing permeability and eventually causing cell death.[131] The bactericidal activity of AgNPs is caused by ROS: smaller AgNPs generate higher levels of ROS.[132] In addition, lipopolysaccharide subunits on the cell membrane and oxygenate groups on GO nanosheets can form abundant hydrogen bonds.[133,134] These bonds bind negatively charged bacteria and GO together, blocking the intake of nutrients by the cells.[135,136] In the presence of trisodium citrate as a stabilizing agent, NaBH4 reduced AgNO3 to AgNPs. The prepared GO/AgNPs suspension induced the leakage of proteins and sugars from the cell wall of B. subtilis and S. aureus, killing the bacteria.[137]

### 3.1.3. rGO-Ag Composite Materials

Reductants are necessary for obtaining rGO and AgNPs. Some reductants can turn GO into rGO and silver-based precursors into AgNPs simultaneously.[138–142] Using the self-polymerization of dopamine (DA), AgNPs were fixed onto the surface of flexible rGO paper. Other than bactericidal activity toward E. coli, this hybrid exhibited a sensitive surface-enhanced Raman scattering response towards Rhodamine 6G.[143] Given that the use of organic solvents limits the application of GO-Ag composites to biomaterials, Shim et al. used supercritical CO2 (scCO2) as a solvent and hydrogen as a reductant to produce Ag nanoparticle-decorated rGO sheets.[144] Analogously, t-ascorbic acid solution vapor can be used as a green reducing agent.[145] To encourage recycling, Fe3O4 NPs were added into an rGO/Ag nanocomposite. In the presence of a magnetic field, the composite was recovered in Ag-sterilized liquid.[90,146] In addition to nanoscrolls, sandwich-like structures have been prepared by inserting dopamine-modified halloysite nanotubes (HNTs) into GO nanosheets to enlarge the surface area of GO. The dopamine molecules acted as a reducing agent to synthesize rGO and as a sorbent of AgNPs after the reduction reaction.[147]

The bactericidal mechanisms of rGO-Ag composite materials combine the effects of rGO and AgNPs. To determine the relationship between the size of AgNPs on rGO nanosheets and antibacterial performance, sequential repetitive reductions of AgNO3 have been sequentially reduced in size on the surface of rGO. The results suggested that NPs with a diameter of 20–30 nm exhibited the highest antibacterial activity, which is related to the interaction between AgNPs and the S/P atoms of bacterial compounds, and the distribution of AgNPs is affected by rGO.[148,149] After coating with AgNPs-decorated rGO nanosheets, carbon foam acted as a bactericidal device driven only by a 1.5 V dry battery. With the ROS released by rGO, the Ag+ produced by electrolysis, direct contact and the effect of the electric field, this device killed E. coli and S. aureus and was used to clean water.[150] Deposited Ag doped flower-shaped ZnO NPs onto the surface of rGO, forming a composite with bactericidal activity that can degrade dye under UV irradiation. With rGO acting as a base and electron acceptor, the NPs can function more effectively.[151] Microwave irradiation was also used as a facile method to prepare Ag-rGO nanocomposites. Because of the synergic effect of rGO and AgNPs, this composite has greater antimicrobial activity towards P. aeruginosa using less Ag.[152]

### 3.2. Graphene and its Derivatives Combined with other Materials for Antibacterial Effects

Apart from Ag, several different types of materials have been tested with graphene and its derivatives to generate improved antibacterial properties. Table 1 summarizes most of the materials that have been combined with graphene derivatives. The main types of interactions...
between graphene and other materials are van der Waals forces, covalent conjugation formed by physical blending and chemical reactions. The honeycomb-like carbon structure on the surface of graphene and its derivatives also enables the π–π stacking of graphene and materials with aromatic rings, such as PVK and TTPs. Those complexes are useful for wound dressing and wastewater treatment.\textsuperscript{[153,154]}

3.2.1. Graphene Combined with other Materials for Antibacterial Effects

Electrospinning is a facile technology used to synthesize porous graphene complex materials. The diameter of fibers prepared by electrospinning can reach the nanometer grade. The electrospun fabrics possess high porosity, a large specific area and a small pore size, favoring the release of loaded
Table 1. Materials incorporated with graphene derivatives.

<table>
<thead>
<tr>
<th>Material</th>
<th>Functionalization</th>
<th>Hybrid components</th>
<th>Type of interaction</th>
<th>Bacteria</th>
<th>Characterization</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>graphene</td>
<td>-</td>
<td>ZnO nanoparticles</td>
<td>van der Waals</td>
<td><em>E. coli</em>, <em>S. mutans</em>, <em>S. typhi</em></td>
<td>XRD, TEM, XPS</td>
<td>[155–158]</td>
</tr>
<tr>
<td>graphene</td>
<td>-</td>
<td>ferrocene precursors</td>
<td>van der Waals</td>
<td><em>E. coli</em></td>
<td>SEM, XRD, Micro Raman, AFM, TEM, HRXPS</td>
<td>[159]</td>
</tr>
<tr>
<td>graphene</td>
<td>-</td>
<td>TiO$_2$</td>
<td>covalent</td>
<td><em>bacteria (E. coli, S. aureus) and fungi (C. albicans)</em></td>
<td>XRD, XPS, TEM, UV–vis absorption FT-IR, FE-SEM Raman</td>
<td>[160–162]</td>
</tr>
<tr>
<td>graphene</td>
<td>-</td>
<td>Au-TiO$_2$ nanocomposite</td>
<td>covalent/van der Waals</td>
<td><em>E. coli</em>, <em>Rhodopseudomonas palustris (PSB), Candida</em></td>
<td>AFM, Raman, FTIR, TEM, UV–Visible</td>
<td>[163]</td>
</tr>
<tr>
<td>graphene</td>
<td>methanol</td>
<td>gentamicin sulfate</td>
<td>hydrogen bonding</td>
<td><em>E. coli</em></td>
<td>XEM, XRD, TGA</td>
<td>[2]</td>
</tr>
<tr>
<td>graphene</td>
<td>-</td>
<td>zinc ferrite/polyaniline (ZnFe$_2$O$_4$/PANI)</td>
<td>covalent</td>
<td><em>S. aureus</em>, <em>E. coli Candida albicans</em></td>
<td>XRD, FTIR, SEM, TEM</td>
<td>[164]</td>
</tr>
<tr>
<td>graphene</td>
<td>-</td>
<td>chlorophenyl</td>
<td>covalent</td>
<td><em>E. coli</em>, <em>S. aureus</em></td>
<td>FTIR, Raman, XPS, XRD</td>
<td>[165]</td>
</tr>
<tr>
<td>graphene</td>
<td>-</td>
<td>PLA, poly (ethylene glycol) (PEG), epoxidized palm oil (EPO)</td>
<td>van der Waals</td>
<td><em>E. coli</em>, <em>S. typhimurium</em>, <em>S. aureus</em>, <em>Listeria monocytogenes</em></td>
<td>TG, DTG, SEM, TEM</td>
<td>[166]</td>
</tr>
<tr>
<td>graphene</td>
<td>-</td>
<td>Fe$_3$O$_4$</td>
<td>van der Waals</td>
<td><em>E. coli</em></td>
<td>TEM, FE-SEM, Protein degradation</td>
<td>[167]</td>
</tr>
<tr>
<td>graphene</td>
<td>-</td>
<td>stannous dioxide (SnO$_2$)</td>
<td>van der Waals</td>
<td><em>Pseudomonas aeruginosa</em>, <em>S. aureus</em></td>
<td>TEM, UV, FTIR, fluorescence, Raman, SEM, EDX, MALDI-MS</td>
<td>[168]</td>
</tr>
<tr>
<td>graphene</td>
<td>GO</td>
<td>chitosan-polyvinyl alcohol (PVA)</td>
<td>van der Waals</td>
<td><em>E. coli</em>, <em>Agrobacterium</em>, yeast cells</td>
<td>SEM, TEM, Raman</td>
<td>[56]</td>
</tr>
<tr>
<td>graphene, GO</td>
<td>-</td>
<td>PK</td>
<td>van der Waals</td>
<td><em>B. subtilis</em>, <em>E. coli</em>, <em>R. opacus</em>, <em>C. metallidurans CH4</em></td>
<td>FT-IR, SEM, AFM, UV, TGA</td>
<td>[169–171]</td>
</tr>
<tr>
<td>GO, rGO</td>
<td>-</td>
<td>chitosan (CS)</td>
<td>van der Waals</td>
<td><em>P. aeruginosa</em>, <em>S. aureus</em></td>
<td>SEM, XRD, DSC, AFM, Raman</td>
<td>[1,172]</td>
</tr>
<tr>
<td>GO, rGO</td>
<td>carboxylate</td>
<td>native lactoferrin (NLf),CS</td>
<td>electrostatic interactions/van der Waals</td>
<td><em>E. coli</em></td>
<td>UV/vis, FTIR, TEM, Raman, XPS, SEM</td>
<td>[173]</td>
</tr>
<tr>
<td>GO carboxylate</td>
<td>-</td>
<td>lanthanum(II)</td>
<td>covalent</td>
<td><em>E. coli</em>, <em>S. aureus</em></td>
<td>TEM, SEM, XPS, XRD, Fluorescence microscopy</td>
<td>[174]</td>
</tr>
<tr>
<td>GO carboxylate</td>
<td>-</td>
<td>benzylpenicillin (BP) anion intercalated Mg–Al layered double hydroxide (BP-LDH)</td>
<td>electrostatic interaction</td>
<td><em>M. lysodeikticus</em>, <em>SRB</em></td>
<td>XRD, FTIR, AFM, TEM, SEM</td>
<td>[176]</td>
</tr>
<tr>
<td>GO, rGO</td>
<td>-</td>
<td>agarose (AG)</td>
<td>covalent</td>
<td><em>E. coli</em>, <em>S. aureus</em></td>
<td>FTIR, Raman, XRD, SEM</td>
<td>[177]</td>
</tr>
<tr>
<td>GO</td>
<td>-</td>
<td>tungsten oxide</td>
<td>covalent</td>
<td>bacteriophage MS2 viruses</td>
<td>AFM, XPS, Raman, SDSP</td>
<td>[178]</td>
</tr>
<tr>
<td>GO</td>
<td>-</td>
<td>poly (N-vinylcarbazole) (PVK)</td>
<td>π–π stacking</td>
<td><em>E. coli</em></td>
<td>CV, ATR IR, AFM, Fluorescence</td>
<td>[179]</td>
</tr>
<tr>
<td>GO</td>
<td>-</td>
<td>polyamide membranes</td>
<td>covalent</td>
<td><em>E. coli</em></td>
<td>AFM, XPS, Raman, SEM</td>
<td>[180]</td>
</tr>
<tr>
<td>GO</td>
<td>-</td>
<td>gramicidin (GD)</td>
<td>van der Waals</td>
<td><em>Pseudomonas aeruginosa</em>, <em>S. aureus</em></td>
<td>TEM, UV, FTIR, SEM, EDX, Fluorescence</td>
<td>[181]</td>
</tr>
<tr>
<td>GO</td>
<td>4,4-methylene diamineline (MDA)</td>
<td>polyethylene/ polyethylene oxide (PE/PEO)</td>
<td>van der Waals</td>
<td><em>E. coli</em></td>
<td>TEM, Raman, XRD, FTIR</td>
<td>[182]</td>
</tr>
<tr>
<td>GO</td>
<td>-</td>
<td>cystamine</td>
<td>π–π conjugated interactions</td>
<td><em>E. coli</em>, <em>S. typhimurium</em>, <em>Bacillus subtilis</em>, <em>Enterococcus faecalis</em></td>
<td>AFM, SEM, UV, XPS</td>
<td>[183]</td>
</tr>
<tr>
<td>GO propargylamine</td>
<td>-</td>
<td>macroporous polypropylene membrane (MPPM)</td>
<td>covalent</td>
<td><em>E. coli</em></td>
<td>FT-IR, XPS, XRD, FESEM</td>
<td>[184]</td>
</tr>
<tr>
<td>GO</td>
<td>-</td>
<td>ZnO</td>
<td>van der Waals</td>
<td><em>E. coli</em></td>
<td>TEM, EDS, XRD, XPS, SEM, AFM</td>
<td>[185–190]</td>
</tr>
<tr>
<td>GO</td>
<td>-</td>
<td>dimethyldioctadecylammonium (DODA)</td>
<td>covalent</td>
<td><em>Pseudomonas aeruginosa</em></td>
<td>SEM, TEM, Raman, Laser scanning confocal microscopy</td>
<td>[191]</td>
</tr>
<tr>
<td>GO propargylamine NaN$_3$</td>
<td>-</td>
<td>macroporous polypropylene membrane (MPPM)</td>
<td>covalent</td>
<td><em>E. coli</em></td>
<td>FT-IR, XRD, XPS, FESEM</td>
<td>[184]</td>
</tr>
</tbody>
</table>
drugs and the migration and proliferation of cells. This type of material is widely used for tissue engineering, drug delivery and medical dressings in the biomedical field. A chitosan (CS)-poly(vinyl alcohol) (PVA) electrospinning nanofiber membrane doped with graphene inhibited the division of prokaryotic E. coli cells and Agrobacterium cells but not eukaryotic yeast cells. This specificity may be due to the differences in the cell structure of prokaryotic and eukaryotic cells (Figure 3d). The nuclear membrane of eukaryotic cells prevents electrons of graphene from entering the nucleus and damaging DNA or other genetic materials. Still, these graphene-containing CS-PVA membranes are generally useful for wound healing because the microbes responsible for wound festering are primarily prokaryotic. Similar to anchoring AgNPs, functionalized graphene is another alternative to complexes. Compared with pristine graphene, modified graphene exhibited improved solubility, reactivity and biocompatibility.

Modified graphene retains the antibacterial physicochemical properties of photothermal stress, oxidative stress and entrapment. As an efficient photocatalyst, graphene focuses heat to kill bacteria in the presence of laser energy, such as NIR. Even daylight can be used as the heat source when the composite is combined with a strong photocatalyst, such as ZnO and ZnFe$_2$O$_4$. This type of material can produce ROS to oxidize and degrade bacteria under irradiation. The effects of ROS have been confirmed by the oxidant-sensitive dyes DCFH-DA and GSH. GSH is a thiol-containing tripeptide that acts as an antioxidant in bacteria. Reduction of the thiol groups (–SH) to disulfide bonds (–S–S–) converts GSH to glutathione disulfide and protects cellular components against oxidants. GSH can be used in the Ellman’s assay to measure oxidants, such as ROS. Iron oxide promotes the adhesion of dyes to bacterial cells, and the graphene component of the graphene-Fe$_3$O$_4$ nanocomposite exhibited tremendous antibacterial activity due to the release of ROS, indicating the potential of this material in water purification applications. Additionally, membrane stress contributes to the bactericidal performance of graphene complexes. With their hydrophobic sp$^2$ carbon atoms, graphene nanosheets strongly interact with cell membranes and can wrap around them. This facilitates the antibacterial activity of agents, such as guanidine, that are delivered on graphene. A PVK-graphene material exhibited high bacterial toxicity and high biocompatibility simultaneously, making it suitable for biomedical devices and implants. In addition to restricting bacterial viability, graphene helps reinforce the mechanical properties of antibacterial composites because of its high Young’s modulus and excellent flexibility.

### 3.2.2. GO Combined with other Complexes for Antibacterial Effects

In addition to van der Waals forces, the interaction forces between GO and other components in a hybrid are mainly electrostatic or conjugated interactions. Because of the negatively charged nature of GO, positively charged materials such as LDH can bind with GO through electrostatic interactions. The carbazole groups of PVK form π–π stacking interactions with GO, stabilizing the dispersion of the nanocomposite and creating a conducting polymer network (CPN) that can be immobilized on any conducting substrate via electrochemical methods. PVK provides a greater aspect ratio by increasing the dispersion of GO in solution, thereby promoting the interaction of bacteria and GO. As a widely used nanocarrier, GO can also be added to other antibacterial agents, such as chitosan, ciprofloxacin and benzalkonium salt, to enhance the antibacterial properties. Fixing drugs on the film enables the slow release of drugs and generates lasting effects. The complexes can be recycled after mixing with magnetic NPs, iron oxide for example. The interaction of GO with bacteria makes GO a potential candidate for detecting bactericidal effects in surface-enhanced Raman scattering (SERS). The GO-wrapped Au nanocluster SERS tags can kill S. aureus and E. coli with the photothermal property, and the process can be detected by SERS. GO

**Table 1. Continued**

<table>
<thead>
<tr>
<th>Material</th>
<th>Functionalization</th>
<th>Hybrid components</th>
<th>Type of interaction</th>
<th>Bacteria</th>
<th>Characterization</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>GO, rGO</td>
<td>4-carboxylic acid benzene diazonium salt (DS)</td>
<td>PLL</td>
<td>electrostatic interaction</td>
<td>E. coli, S. aureus</td>
<td>FTIR, XPS, SEM</td>
<td>[192]</td>
</tr>
<tr>
<td>rGO</td>
<td>magnetic NPs</td>
<td>glutaraldehyde (GA)</td>
<td>covalent</td>
<td>E. coli, S. aureus</td>
<td>TEM, FTIR, UV vs. NIR, SEM, CLSM</td>
<td>[193]</td>
</tr>
<tr>
<td>rGO</td>
<td>poly-γ-lysine (PLL)</td>
<td>copper nanoparticles (CuNPs)</td>
<td>π–π conjugated interactions</td>
<td>E. coli, S. aureus</td>
<td>XPS, UV/vis, Fluorescence, Raman, FTIR, TEM</td>
<td>[194]</td>
</tr>
<tr>
<td>rGO</td>
<td>brilliant blue (BB)</td>
<td>tetradecyltriphenylphosphonium bromide (TTP)</td>
<td>π–π conjugated interactions</td>
<td>E. coli, S. aureus</td>
<td>XPS, UV/vis, Fluorescence, Raman, FTIR, TEM</td>
<td>[195]</td>
</tr>
<tr>
<td>rGO</td>
<td>-</td>
<td>rhombus-shaped ZnMoO$_x$</td>
<td>covalent</td>
<td>E. coli</td>
<td>XRD, FTIR, SEM, TEM</td>
<td>[196]</td>
</tr>
<tr>
<td>rGO</td>
<td>-</td>
<td>PE</td>
<td>hydrogen bonding</td>
<td>S. aureus, Bacillus subtilis, E. coli, Pseudomonas aeruginosa, Klebsiella pneumonia</td>
<td>FTIR, XRD, SEM, AFM, TGA, DSC, tensile strength measurements</td>
<td>[197]</td>
</tr>
<tr>
<td>rGO</td>
<td>-</td>
<td>exfoliated layered titanate nanosheets</td>
<td>van der Waals</td>
<td>E. coli</td>
<td>XRD, STEM–BF, STEM–HAADF, XANES, EXAFS, FE-SEM</td>
<td>[198]</td>
</tr>
<tr>
<td>rGO</td>
<td>-</td>
<td>hyaluronic acid and polyelec- electrostatic interaction trolute poly-γ-lysine (HA/PLL)</td>
<td>E. coli</td>
<td>AFM, Plastic strain distribution, plane view, TEM, Raman</td>
<td>[199]</td>
<td></td>
</tr>
</tbody>
</table>
nanosheets can be impregnated with photocatalysts to prepare versatile composites. With the antibacterial ability of GO and photocatalytic degradation ability of the catalyst, the composites are useful for water purification.\textsuperscript{[217–219]} Porous structures that exhibit enhanced performance are useful in many applications, such as templates for cell growth and...

tissue formation in biomaterials applications or as selective organic absorbents in environmental remediation. [220–222]

Through an “on-water spreading” method, GO and dimethylidioctadecylammonium (DODA) complexes formed free-standing porous honeycomb films that exhibited excellent antibacterial activity toward \textit{P. aeruginosa} PAO1 and \textit{E. coli} (Figure 7). [191] A GO-modified macroporous polypropylene membrane (MPPM) was synthesized with layer-by-layer
assembly and click chemistry. The resulting antifouling and dye removal membrane material are ideal for water purification. Complexes containing GO can be electrospun into porous nanofiber mats as well. GO enhanced not only the antibacterial properties but also the tensile strength of fiber membranes.

Oxidative and membrane stress contribute to the antibacterial performance of GO hybrid materials. For modified GO and pristine GO, the release of ROS was dependent on concentration and was affected by external factors in DCFH-DA and GSH experiments. PVK-graphene or PVK-GO was impregnated onto commercially available membrane filters to impart antibacterial properties. Due to the large amount of ROS produced by PVK-GO, the membrane filters containing PVK-GO exhibited improved removal of E. coli and B. subtilis. Different microorganisms have different levels of tolerance toward PVK-GO and pristine GO materials. The Gram-negative bacterium Cupriavidus metalidurans CH4 exhibited greater inactivation when treated with GO than with the same concentration of PVK-GO, whereas the Gram-positive bacteria B. subtilis and Rhodococcus opacus exhibited contrasting results. These differences were attributed to the bacterial cell wall, the surface protective effect of the outer membrane, and the ability to respond to the external environment. Membrane stress produced by the sharp edges of GO nanosheets also contributes to the antibacterial and antifouling performance of the complexes.

3.2.3. rGO Combined with other Complexes for Antibacterial Effects

The antibacterial properties of rGO hybrid materials were affected by membrane stress, oxidative stress and the photothermal effect. After adding agarose (AG) for physical crosslinking and reduction, rGO formed a type of dye-adsorbing and antibacterial hydrogel (Figure 6). A water-solubilized brilliant blue (BB)-rGO composite has been applied as a drug carrier for TTPs via π–π interactions. When the BB-rGO-TTP composite contacted E. coli or S. aureus, the blade-like edges of rGO first damaged the cytoplasmic membrane of the bacteria; then, the poison TTP was released into the cytoplasm. The synergistic effect of BB, rGO and TTP yielded an efficient, water-soluble, specific, mildly cytotoxic antimicrobial agent. The ROS-related antibacterial effect of rGO complexes is time and concentration dependent. However, after comparing the results of antibacterial activity, ROS generation, and the GSH oxidation assay, the antibacterial property of rGO-titanate hybrid films was attributed to neither ROS-dependent oxidative stress nor ROS-independent oxidative stress but to the photocatalytic activity of the titanate component. Two types of core-shell structured photocatalysts have been prepared using a heat-etching method. One catalyst was rGO wrapping g-C3N4 (CN) sheets and cyclooctasulfur (α-S8), and the other was CN wrapping rGO and α-S8. Due to the electron conductivity of rGO and photocatalysis of α-S8 and CN, the two photocatalysts showed excellent but different bacteria inactivation properties in visible light. The E. coli cells were inactivated by oxidative stress under aerobic conditions and by reduction stress under anaerobic conditions. With its photothermal properties, rGO can focus heat to kill bacteria in the presence of NIR. The rare-earth/rGO hybrid effectively killed clinical drug-resistant bacteria after tracking them. A “layer-by-layer” method was applied to deposit porous rGO coatings, hyaluronic acid (HA) and polyelectrolyte poly L-lysine (PLL) onto a substrate. The introduced rGO exhibited antibacterial properties and other unique physiochemical properties, and only low levels of platelet aggregation were observed, indicating the potential of the porous material for cardiovascular therapy.

3.2.4. GQDs Combined with other Complexes for Antibacterial Effects

Acting as a peroxidase, GQDs catalyze the degradation of loaded H2O2 into bactericidal ·OH, making the hybrid useful for wound disinfection without the toxicity of high concentrations of H2O2. GQDs can act as an antifouling coating by covalently bonding with polyvinylidene fluoride (PVDF) membranes. This complex exhibited the same insertion and extraction effect as graphene against phospholipid molecules in bacterial membranes.

4. Conclusions, Challenges and Perspectives

The antibacterial effects of graphene, its derivatives and their hybrids, particularly the hybrids combined with AgNPs, are summarized and discussed in this article. The bactericidal effects of graphene and its derivatives are attributed to ROS stress, membrane stress, entrapment, electron transfer and a photothermal effect. Briefly, ROS oxidize the cellular components of bacteria, such as lipids, DNA and proteins. Membrane stress and electron transfer damage the integrity of bacterial membranes, leading to leakage of cellular contents. Entrapment isolates bacteria from gases and nutrients, preventing their proliferation. The photothermal effect raises the temperature of the surrounding environment to kill bacteria. These factors depend on the physiochemical properties of graphene and its derivatives, including their layers, surfaces, lateral dimensionality, sharp edges and oxygenated groups.

With a high specific surface area, reactive groups and a honeycomb-like atomic structure, graphene and its derivatives are typically used as substrates for AgNPs to decrease aggregation and improve synergetic antibacterial activity. AgNP-decorated graphene and its derivatives have prominent antibacterial properties. The use of graphene and its derivatives as substrates prevents agglomeration and enhances the stability of Ag particles. The modified surfaces and physiochemical properties of graphene and its derivatives also help regulate the size of Ag particles, promoting the antibacterial activity of Ag. These properties, including the synergistic effect of AgNPs with graphene and its derivatives, enhance the antibacterial activity of graphene or...
Graphene derivatives combined with Ag composite materials. Graphene and its derivatives interact with various materials through covalent, electrostatic or conjugate attachments, making them a perfect substrate to combine with different types of materials. Although the interpretations of hybrid antibacterial mechanisms remain controversial, the hybrids clearly have potential antibacterial applications. These antibacterial materials show great potential in medicine, food, and water purification. The impressive work described above clearly have potential antibacterial applications. These antibacterial mechanisms remain controversial, the hybrids making them a perfect substrate to combine with different materials in food industry, biomedical engineering and daily chemical. Although some practical applications of graphene and its derivatives have been made, extensive researches are needed to transform more of these theoretical studies into practical applications. Due to their unique characteristics, graphene and its derivatives will continue to be a hotspot of antibacterial research.

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