Recent advances in graphite carbon nitride-based nanocomposites: structure, antibacterial properties and synergies

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Bacterial infections and transmission threaten human health and well-being. Graphite carbon nitride (g-C\textsubscript{3}N\textsubscript{4}), a promising photocatalytic antibacterial nanomaterial, has attracted increasing attention to combat bacterial transmission, due to the outstanding stability, high efficiency and environmental sustainability of this material. However, the antibacterial efficiency of g-C\textsubscript{3}N\textsubscript{4} is affected by several factors, including its specific surface area, rapid electron/hole recombination processes and optical absorption properties. To improve the efficiency of the antibacterial properties of g-C\textsubscript{3}N\textsubscript{4} and extend its range of applications, various nanocomposites have been prepared and evaluated. In this review, the advances in amplifying the photocatalytic antibacterial efficiency of g-C\textsubscript{3}N\textsubscript{4}-based nanocomposites is discussed, including different topologies, noble metal decoration, non-noble metal doping and heterojunction construction. The enhancement mechanisms and synergistic effects in g-C\textsubscript{3}N\textsubscript{4}-based nanocomposites are highlighted. The remaining challenges and future perspectives of antibacterial g-C\textsubscript{3}N\textsubscript{4}-based nanocomposites are also discussed.

1. Introduction

Bacterial infections and their transmission pose a considerable threat to human health, usually leading to delayed wound healing and chronic intestinal diseases.\textsuperscript{1,2} Furthermore, pathogenic bacteria frequently contaminate water supplies and the soil, resulting in the death of animals and plants through environmental contamination.\textsuperscript{3} To address these problems, antibiotics are widely used to kill bacteria, but over-utilization of antibiotics can bring about resistance and secondary contamination.\textsuperscript{4–6} Therefore, the development of new strategies...
to inactivate bacteria without using antibiotics is urgently required as is the inactivation of drug-resistant bacteria. In recent years, semiconductor photocatalysis has attracted significant interest for applications in pollutant degradation and antimicrobial applications. Under sunlight irradiation, semiconductor photocatalysts react with water and oxygen to form reactive oxygen species (ROS), such as hydrogen peroxide (H2O2), hydroxyl radicals (·OH) and superoxide (O2·−), which are able to inactivate bacteria by oxidizing the phospholipid membrane, proteins and nucleic acids. Common photocatalysts include metallic oxides, sulfides, nitrides, and phosphides, and graphene and its derivatives, which show bactericidal activity against both Gram-positive and Gram-negative bacteria, as demonstrated in many studies. However, relatively narrow spectral absorption ranges result in low efficiencies. Together with other problems such as facile aggregation, potential toxicity, and low biocompatibility, practical application of these common photocatalysts is limited. As an emerging non-metallic photocatalyst, graphitic carbon nitride (g-C3N4) is easy to prepare and has an appropriate band structure and good biocompatibility, thus showing considerable potential as antibacterial materials.

Similar to the layered structure of graphene, g-C3N4 is a polymeric layered material which consists of carbon and nitrogen with some hydrogen (impurity). The conduction band (CB) and valence band (VB) position of g-C3N4 are ~1.13 and 1.57 eV, respectively. The appropriate band gap is about 2.70 eV, i.e. it is a medium band gap semiconductor, readily obtained from the pyrolysis of melamine, dicyandiamide or urea. Benefiting from the connection of tri-s-triazine units through tertiary amines (Fig. 1), g-C3N4 has a two-dimensional flake structure. The adjacent g-C3N4 flakes interact weakly with each other via van der Waals forces, displaying a layer gap of about 0.33 nm. Thus, when such forces between the bulk g-C3N4 layers are broken, paper-like g-C3N4 nanosheets are obtained. From a molecular prospective, C3N4 is considered to have two main molecular structures. One comprises a triazine with a tertiary nitrogen atom in the center of a planar triangle (Fig. 1a) that connects three separate triazine rings in an infinitely repeating pattern. Another is a tri-s-triazine structurally connected to form g-C3N4 (Fig. 1b). This more stable tri-s-triazine structure is commonly used as the structural unit of g-C3N4. These excellent structural features and properties make C3N4 a promising photocatalytic material. Since the first study of the photocatalytic activity of g-C3N4 by Wang et al. in 2009, it has become a prevalent photocatalytic material. Due to the merits of the non-metallic g-C3N4 material, such as a wide visible light absorption range, excellent chemical stability and low toxicity, it has been widely studied to tackle environmental and energy related problems. Specifically, g-C3N4 has been used as a catalyst for photocatalytic water reduction and oxidation, contaminant degradation and carbon dioxide reduction. For photocatalytic degradation, the photoproduced electrons (e−) and holes (h+) can accelerate reduction and oxidation degradation reactions. In addition, the e− and h+ can react with surrounding H2O and O2 to generate ROS such as ‘O2·−’ and ‘OH·’. The generated ROS can further degrade pollutants, combining to achieve the removal of contaminants.

In this review, several tactics for enhancing the antimicrobial efficiency of g-C3N4-based nanocomposites are discussed, including the design of different g-C3N4 topologies, noble metal decoration, non-noble metal doping and heterojunction construction. These approaches have been shown to effectively boost the antibacterial activity of g-C3N4. The enhancement mechanisms and synergistic effects of g-C3N4-based nanocomposites is highlighted. Additionally, photocatalytic mechanisms have been elucidated by analyzing the interactions between the nanomaterials and bacteria.
Lastly, this review concludes by defining future prospects, opportunities and challenges in this exciting field.

2. g-C₃N₄-based materials and their photocatalytic antibacterial

Both the nitrogen and carbon atoms in g-C₃N₄ are sp² hybridized to form a conjugated structure with delocalized π-electrons, giving g-C₃N₄ the lowest bandgap compared to other phases of C₃N₄. Compared to other conventional photocatalytic materials, g-C₃N₄ has a narrow band gap (2.7 eV), resulting in a wider spectral absorption range of up to 460 nm, and improving the photocatalytic window. The photocatalytic reactions of g-C₃N₄ affect its antibacterial performance. When the energy of the visible light illuminating g-C₃N₄ is larger than the band gap energy of g-C₃N₄, e⁻ are promoted from the valence band (VB) to the conduction band (CB), producing active e⁻ and h⁺. However, the e⁻/h⁺ can recombine on the g-C₃N₄ surface. Alternatively, the e⁻/h⁺ pairs diffuse or are transported to the g-C₃N₄ interface by an electric field and undergo redox reactions with the surroundings. As shown in Fig. 3, under visible light illumination, g-C₃N₄ produces ROS that can destroy the bacterial membranes, causing cell membrane permeability, structural degradation and ultimately killing the bacterial.

| Reactions |
| --- |
| g-C₃N₄ | g-C₃N₄ (h⁺ + e⁻) |
| O₂ + e⁻ | O₂⁻ |
| H₂O + h⁺ | OH⁻ + H⁺ |
| Bacterial membrane + h⁺(OH⁻O₂⁻) | products |

Fig. 3 Plausible reactions between bacterial and g-C₃N₄-based nanocomposite generated ROS.

2.1 Influence of topology on g-C₃N₄-based antibacterial photocatalysts

The antibacterial activity of g-C₃N₄ is influenced by its topology, in particular, the efficiency of bulk g-C₃N₄ is restricted by its small superficial area and rapid rate of recombination of photogenerated carriers. In contrast, mesoporous g-C₃N₄, g-C₃N₄ nanotubes and nanosheets absorb visible light more effectively and provide a larger contact area for reactions because of their larger specific surface areas and a larger number of active sites. In addition, these structures decrease the distance required for the transfer of the charge to the surface of the material, decreasing charge recombination. Moreover, due to the quantum size effects, g-C₃N₄ nanosheets are suited to charge transfer and separation processes. Therefore, g-C₃N₄ nanosheets and their composite materials show promising photocatalytic antibacterial properties. Li et al. developed a self-cleaning antibacterial membrane by simply filtering g-C₃N₄ nanosheets into polyacrylonitrile porous substrates (Fig. 4a), then forming a stable coating by cross-linking polyvinyl alcohol and glutaraldehyde. In contrast to membranes without g-C₃N₄ nanosheets, the membranes containing the g-C₃N₄ nanosheets (0.45 wt%) completely inactivated 1 × 10⁶ cfu mL⁻¹ E. coli under irradiation with visible light (Fig. 4b and c). The high superficial area of the g-C₃N₄ nanosheets in the membrane provides more active sites that produce ROS for sterilization. Meanwhile, the membranes with g-C₃N₄ nanosheets also showed good permeability to water and degraded dyes. Compared to g-C₃N₄ nanosheets, nanotubes have high aspect ratios, a topology that favors the migration of e⁻ along the axial direction and inhibits the lateral transfer of e⁻, thereby inhibiting the recombination of photogenerated carriers. Moreover, nanotubes usually have large specific surface areas, providing a higher density of active sites at their surface, which improves photocatalytic antibacterial performance. Xu et al. successfully synthesized microtubular nanoporous g-C₃N₄ with a layered structure and nitrogen defects using molecular self-assembly methods. The hexagonal tubular structure promotes the multiple use of light, and provides a larger density active sites and a directional transfer channel for e⁻. Moreover, the nanoporosity of the material increases the specific surface area to provide rich charge transport paths. In addition, the nitrogen vacancies improve the light harvesting properties of the material (λ > 450 nm) and promote charge separation by trapping charge. Hence, microtubular nanoporous g-C₃N₄ completely inactivated 5 × 10⁶ cfu mL⁻¹ E. coli after 4 h of light illumination, compared to only 74% of E. coli sterilized by bulk g-C₃N₄. Hollow porous microspheres not only promote light penetration within the material and light absorption at the pore edges, but also provide sufficient contact area to accelerate interfacial charge transfer. In addition, the thinner pore wall structure reduces the distance (and time) required for charge transfer within the material, decreasing the recombination of photogenerated carriers. Yang et al. successfully fabricated a self-cleaning, antimicrobial and antifouling membrane by integrating mesoporous g-C₃N₄ (MCN) into polyvinylidene fluoride.
The mesoporous structure promotes multiple reflections of incident light and enhances the capacity of the material for light capture, leading to an enhancement in the generation of $h^+$ and ROS. The MCN-PVDF membrane showed a significant reduction in the number of E. coli colonies under illumination with visible light over 4 hours, with approximately 3 log deactivation of E. coli.$^{88,89}$ In contrast, an analogous experiment using a membrane-free material showed no significant decrease.

Table 1  Antibacterial properties of g-C$_3$N$_4$ based materials with different topologies

| Material                  | Preparation                                           | Bacteria                  | Effect       | Ref. |
|---------------------------|-------------------------------------------------------|---------------------------|--------------|-----|
| g-C$_3$N$_4$ nanosheets   | Acid etching and ultrasound                           | E. coli                  | ~100%        | 82  |
| Microtubular nanoporous g-C$_3$N$_4$ | Molecular self-assembly                              | E. coli                  | 99.2%        | 85  |
| g-C$_3$N$_4$ nanosheets   | Freezing and microwave-assisted                       | E. coli                  | 100%         | 90  |
| Porous g-C$_3$N$_4$ nanosheets | Template-free                                     | E. coli                  | 100%         | 91  |
| g-C$_3$N$_4$ nanosheets   | Bacterial etching                                     | E. coli                  | 3.65 log     | 92  |
| g-C$_3$N$_4$ nanosheets   | Ultrasound                                            | E. coli O157:H7           | 0.82 log     | 93  |
| g-C$_3$N$_4$ nanosheets   | Chemical exfoliation                                  | S. aureus                | 0.85 log     | 93  |
| g-C$_3$N$_4$ nanosheets   | Ultrasound                                            | E. coli K-12             | 6.5 log      | 94  |
| bare g-C$_3$N$_4$          | Calcination                                           | E. coli                  | 99%          | 95  |
| Mesoporous g-C$_3$N$_4$    | Immersion-precipitation phase transformation          | MS2                      | 100%         | 96  |
| Mesoporous g-C$_3$N$_4$    | Template method                                       | E. coli K-12             | 3 log        | 87  |
| Mesoporous g-C$_3$N$_4$    | Thermal polymerization and selective dialysis approach| E. coli                  | 99%          | 98  |
| Mesoporous g-C$_3$N$_4$    | Self-assembly                                         | S. aureus                | 90%          |     |
| Ag$_2$WO$_4$/mesoporous g-C$_3$N$_4$ | Polymerization                                      | E. coli                  | 100%         | 99  |
| GO quantum dots/oxidized nanoporous g-C$_3$N$_4$ | Self-assembly                                   | E. coli                  | 99.6%        | 100 |
| Nanomesh g-C$_3$N$_4$      | Template method                                       | E. coli K-12             | 85%          | 101 |
| CuInSe$_2$/Zn/g-C$_3$N$_4$/TiO$_2$ nanowire | In situ growth                                      | S. aureus                | 90%          | 102 |
| Mesoporous g-C$_3$N$_4$    | Thermal, polycrystallization                         | E. coli                  | Effective    | 103 |
| Porous g-C$_3$N$_4$        | Calcination                                           | S. aureus                | 99%          | 104 |
| Mesoporous g-C$_3$N$_4$    | Calcination                                           | E. coli                  | Effective    | 105 |
| Nanostructured g-C$_3$N$_4$ | Calcination                                         | E. coli O157:H7          | 97.1%        | 106 |
| Mesoporous g-C$_3$N$_4$    | Hydrothermal                                          | S. aureus                | 93.7%        | 108 |
| g-C$_3$N$_4$ powder        | Calcination                                           | E. coli                  | Effective    | 107 |
| g-C$_3$N$_4$ powder        | Calcination                                           | S. epidermidis            | Effective    | 108 |
in *E. coli* communities over the same time period. Additionally, under visible light, MCN-PVDF degrades the antibiotic cefotaxime (CFX) with a degradation rate of over 97% over five cycles.

When g-C₃N₄ has a large specific surface area its photocatalytic performance is enhanced, e.g. in g-C₃N₄ nanosheets and nanotubes, which have a high density active sites. Furthermore, g-C₃N₄ nanocomposites inhibit e⁻/h⁺ pair recombination and have high charge transfer efficiency due to enhanced visible light absorption. Hence, discrepant topologies of g-C₃N₄ should have outstanding antibacterial performance and the discrepant topologies of g-C₃N₄-based materials and their corresponding antibacterial properties are summarized in Table 1.

### 2.2 Noble metal decorated g-C₃N₄ nanocomposites

Another strategy used to increase the antibacterial performance of g-C₃N₄ involves modification with noble metal nanoparticles, including silver and gold nanoparticles. Surface Plasmon Resonance (SPR) of nanoparticles enhances antibacterial efficiency, by extending the spectral absorption range and promoting the formation of photogenerated carriers in g-C₃N₄. Additionally, noble metal nanoparticles act as electron traps, capturing free e⁻ and thus inhibiting the...
recombination of photogenerated carriers.\textsuperscript{115–118} Ma et al. developed Ag@g-C\textsubscript{3}N\textsubscript{4} nanocomposites by combining thermal polymerization with photo-assisted reduction.\textsuperscript{119} A synergistic antibacterial efficiency was achieved with superior sterilization activity of the Ag@g-C\textsubscript{3}N\textsubscript{4} nanocomposite compared to pure g-C\textsubscript{3}N\textsubscript{4} (Fig. 5f). Ag(0.3 wt%)/g-C\textsubscript{3}N\textsubscript{4} exhibited prominent antibacterial performance and suppressed \textit{E. coli} replication (7.41 log) with only 1.25 h of visible light illumination. In contrast, pure g-C\textsubscript{3}N\textsubscript{4} displayed very low inactivation, with only about (0.4 log) \textit{E. coli} killed following 1.5 h of illumination by visible light (Fig. 5g). Notably, the loading of noble Ag nanoparticles on the g-C\textsubscript{3}N\textsubscript{4} nanosheets significantly increases the visible light absorption region due to the SPR effect of the Ag nanoparticles and the charge transfer between the Ag and the g-C\textsubscript{3}N\textsubscript{4} nanosheets.\textsuperscript{120} Similarly, the strong and unique surface plasmon resonance (SPR) absorption of gold nanoparticles covers a wide range of spectra, including the visible and near-infrared light (NIR).\textsuperscript{121,122} As shown in Fig. 5a, Dai et al. utilized 5–10 nm sized Au nanoparticles to modify g-C\textsubscript{3}N\textsubscript{4} via liquid-phase exfoliation of g-C\textsubscript{3}N\textsubscript{4} combined with the photo-deposition of Au nanoparticles.\textsuperscript{123} When a mixture of \textit{E. coli} and the Au@g-C\textsubscript{3}N\textsubscript{4} nanocomposite were irradiated at 670 nm the resulting ROS effectively kill the bacteria. The viability of the bacteria continually diminishes over the illumination period (Fig. 5b–e). The incorporation of Au nanoparticles into the g-C\textsubscript{3}N\textsubscript{4} nanosheets strikingly improves photocatalytic ROS generation, due to the application of 670 nm light.\textsuperscript{124} In general, noble metal/g-C\textsubscript{3}N\textsubscript{4} nanocomposites significantly outperform unmodified g-C\textsubscript{3}N\textsubscript{4} in antimicrobial experiments, and provide a viable photocatalytic disinfection method, see Table 2 for a summary.

### 2.3 Non-noble metal doped g-C\textsubscript{3}N\textsubscript{4} nanocomposites

While g-C\textsubscript{3}N\textsubscript{4} nanocomposites with noble metals have been shown to improve the photocatalytic antibacterial properties of the material, the high cost of noble metals prohibits widespread applications.\textsuperscript{125–129} Thus, g-C\textsubscript{3}N\textsubscript{4} nanocomposites derived from inexpensive and abundant elements that are non-toxic would be advantageous.\textsuperscript{130–134} In such materials the g-C\textsubscript{3}N\textsubscript{4} band gap may even be reduced to improve the separation efficiency of photogenerated carriers and the photoabsorption region may even be expanded to further improve the photocatalytic antibacterial performance.\textsuperscript{135–142} Surface engineering of carbon-based materials has been an effective tool for construction of materials with special functions.\textsuperscript{143–149} Advantageously, Lewis basic N-sites on the surface g-C\textsubscript{3}N\textsubscript{4} allow strong interactions with Lewis acids, i.e. zinc ions, similar to that observed for other materials.\textsuperscript{150–157} For example, g-C\textsubscript{3}N\textsubscript{4}–Zn\textsuperscript{2+}@graphene oxide (SCN–Zn\textsuperscript{2+}@GO) were prepared using chemical vapor deposition (CVD).\textsuperscript{158} The bidentate ligand, SCN, may coordinate to the Zn\textsuperscript{2+} ions to form cross-links with GO, and additionally changing the crystal structure of g-C\textsubscript{3}N\textsubscript{4} and introducing defect sites (Fig. 6a). The resulting SCN–Zn\textsuperscript{2+}@GO nanocomposite possessed excellent antibacterial activity. Irradiation at 808 nm (NIR) led to heating and irradiation at 660 nm resulted in the generation of ROS and the combination of photothermal and photodynamic processes effectively killed bacteria within a short time (almost quantitatively under the conditions employed). In Fig. 6b and d, the \textit{E. coli} and \textit{S. aureus} blank groups possess unbroken topologies, with glossy bacteria membranes and intact intra-cell structures. The membrane structures of both \textit{E. coli} and \textit{S. aureus} are ruptured under 808 nm and 660 nm light illumination. The intra-cell density decreases and part of cytoplasm overflows

### Table 2 Antibacterial properties of noble metal decoration and non-noble metal doped g-C\textsubscript{3}N\textsubscript{4} nanocomposites

| Main component | Material | Preparation | Bacteria | Effect | Ref. |
|----------------|----------|-------------|----------|--------|------|
| Noble metal decoration | Ag@g-C\textsubscript{3}N\textsubscript{4} | Thermal polymerization and photo-assisted reduction | \textit{E. coli} | 7.41 log | 119 |
| | Ag@g-C\textsubscript{3}N\textsubscript{4} | Single-pot, microemulsion | \textit{E. coli} | 9.95 log | 166 |
| | Ag/P@g-C\textsubscript{3}N\textsubscript{4} | Pyrolysis and green reduction. | \textit{E. coli} | 7 log | 167 |
| | Ag/polydopamine@g-C\textsubscript{3}N\textsubscript{4} | Ultrasound and freeze-drying | \textit{E. coli} | Effective | 168 |
| | Ag/oxidized porous g-C\textsubscript{3}N\textsubscript{4} | Photo-assisted, reduction | \textit{S. aureus} | 99% | 169 |
| | Ag@g-C\textsubscript{3}N\textsubscript{4} | Biogenic, methodology | \textit{E. coli} | Effective | 174 |
| | Ag@g-C\textsubscript{3}N\textsubscript{4} | Calcination | \textit{S. aureus} | Effective | 175 |
| | Ag@g-C\textsubscript{3}N\textsubscript{4} | Photo-deposition method | \textit{P. aeruginosa} | Effective | 177 |
| | Au@g-C\textsubscript{3}N\textsubscript{4} | Liquid-phase, exfoliation and photodeposition | \textit{E. coli} | Effective | 123 |
| | Au@g-C\textsubscript{3}N\textsubscript{4} | Deposition–precipitation | \textit{E. coli} | 82% | 170 |
| | Au@g-C\textsubscript{3}N\textsubscript{4} | Calcination | \textit{S. aureus} | 79% | 176 |
| Non-noble metal doping | g-C\textsubscript{3}N\textsubscript{4}–Zn\textsuperscript{2+}@graphene | Chemical vapor deposition and ultrasonic dispersion | \textit{S. aureus} | 99% | 158 |
| | CQDs@g-C\textsubscript{3}N\textsubscript{4} | Impregnation | \textit{S. aureus} | 7 log | 165 |
| | Fullerene@g-C\textsubscript{3}N\textsubscript{4} | Hydrothermal method | \textit{E. coli} O157:H7 | 86% | 171 |
| | S-CQD/hollow tubular g-C\textsubscript{3}N\textsubscript{4} | Self-assembly and ultrasound | \textit{E. coli} | 6.88 log | 172 |
| | Ag/P/Co/S@g-C\textsubscript{3}N\textsubscript{4} | Calcination | \textit{E. coli} | 7 log | 173 |

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Fig. 6  (a) Preparation of SCN–Zn²⁺@GO. TEM topology of S. aureus (b) and E. coli (c) as control, (d) and (e) following treatment with SCN–Zn²⁺@GO 20% after 10 min irradiation with visible light (the red arrows indicate protein leakage and the dark arrows indicate rupture or ruffling of the bacterial membrane). (f) Antibacterial mechanism of SCN–Zn²⁺@GO 20% under 808 or 660 nm irradiation of ROS and hyperthermia. Reproduced from ref. 158 with permission from WILEY-VCH, copyright 2018. (g) Structural models of the g-C₃N₄ (001) surface, CoB-(010) surface and CoB/g-C₃N₄ after geometry optimization. (h) The mechanism of S. aureus bacteria inactivation in the presence of CoB/g-C₃N₄ under visible light. Reproduced from ref. 159 with permission from the American Chemical Society, copyright 2019.
| Material | Preparation | Bacteria       | Effect | Ref. |
|----------|-------------|----------------|--------|------|
| Bi$_2$S$_3$/g-C$_3$N$_4$ | Ultrasound | E. coli | 99.6% | 185 |
| Red P/g-C$_3$N$_4$ | Sonochemical | E. coli K-12 | 7 log | 186 |
| Perylene diimide/oxygen-doped g-C$_3$N$_4$ | In situ electrostatic assembling | S. aureus | 99.6% | 196 |
| Bi$_2$MoO$_6$/g-C$_3$N$_4$ | In situ solvothermal | E. coli | 100% | 199 |
| MnO$_2$/g-C$_3$N$_4$ | Thermal vapor liquid-polymerization and redox | E. coli | 99.96% | 212 |
| TiO$_2$/kaolinite/g-C$_3$N$_4$ | Sol–gel method | S. aureus | 2.9 log | 220 |
| Ag/AgBr@g-C$_3$N$_4$/nitrogen-doped graphene aerogel | Hydrothermal and freeze-drying | E. coli | ~6 log | 252 |
| Ag$_2$WO$_4$/Ag@g-C$_3$N$_4$ | Ultrasound | E. coli | 90% | 222 |
| Bi$_2$MoO$_6$/Ag@g-C$_3$N$_4$ | Hydrothermal method | E. coli | Effective | 259 |
| Ni$_3$P@g-C$_3$N$_4$ | In situ anchoring and hydrothermal | E. coli K-12 | 7 log | 255 |
| m-Bi$_2$O$_3$/g-C$_3$N$_4$ | Hydrothermal | E. coli K-12 | 6 log | 223 |
| Vanadium modified g-C$_3$N$_4$/TiO$_2$ | Calcination and ultrasonic | E. coli | Effective | 256 |
| BiVO$_3$/Ag@g-C$_3$N$_4$ | Photodeposition and hydrothermal | E. coli | 6.5 log | 225 |
| Ag/ZnO@g-C$_3$N$_4$ | Thermal polymerization and solvothermal | E. coli | 7.4 log | 226 |
| Ag/ZnO@g-C$_3$N$_4$ | Thermal polymerization and solvothermal | E. coli | 6.19 log | 257 |
| Ag$_2$WO$_4$/Ag@g-C$_3$N$_4$ | Hydrothermal and situ reductive | E. coli | 3.05 log | 258 |
| Bi$_2$MoO$_6$/Ag@g-C$_3$N$_4$ | Hydrothermal method | E. coli | Effective | 259 |
| α-Fe$_2$O$_3$/CeO$_2$/g-C$_3$N$_4$ | Hydrothermal method | E. coli | Effective | 260 |
| CuS@g-C$_3$N$_4$ | Electrostatic adsorption | E. coli | 99% | 250 |
| CuO@g-C$_3$N$_4$ | Sol–gel method | Salmonella H9812 | 96% | 251 |
| Bi$_2$O$_3$/g-C$_3$N$_4$ | In situ generation | E. coli | 96% | 251 |
| Vanadate QDs@g-C$_3$N$_4$ | Chemical precipitation | E. coli | 7 log | 262 |
| Cu$_2$O/g-C$_3$N$_4$ | Hydrothermal method | E. coli | Effective | 263 |
| Cu$_2$O/g-C$_3$N$_4$ | Hydrothermal method | E. coli | Effective | 263 |
| TiO$_2$ nanofibers/Ag@g-C$_3$N$_4$ | Ultrasound | E. coli | 99% | 264 |
| Ag/AgCl@g-C$_3$N$_4$ | In situ implanting and anchoring | Tetracycline-resistant bacteria | 100% | 265 |
| γ-Fe$_2$O$_3$/Ag/AgCl@g-C$_3$N$_4$ | Solvothermal and photodeposition | E. coli | 5.59 log | 266 |
| RGO/CA@g-C$_3$N$_4$ | Ultrasonification | E. coli | 6.5 log | 267 |
| TiO$_2$/CuBA@g-C$_3$N$_4$ | Ultrasound | E. coli | Effective | 268 |
| Ag$_2$ZrO$_3$/Ag@g-C$_3$N$_4$ | Co-precipitation | E. coli | 97% | 189 |
| Ag$_2$ZrO$_3$/Ag@g-C$_3$N$_4$ | Adsorption deposition | E. coli | 6.5 log | 269 |
| BiFeO$_3$/Cu$_2$O@g-C$_3$N$_4$ | Hydrothermally and ultrasonic | E. coli | Effective | 270 |
| ZnO@g-C$_3$N$_4$/cellulose | Ultrasound irradiation | E. coli | Effective | 271 |
| CdS@g-C$_3$N$_4$ | Sonochemical | E. coli | Effective | 272 |
| GO@g-C$_3$N$_4$ | Sonication | E. coli | 97.9% | 70 |
| AgCl/CNTs@g-C$_3$N$_4$ | Deposition–precipitation | E. coli | Effective | 273 |
| MoO$_3$@g-C$_3$N$_4$ | Hydrothermal | E. coli | 100% | 274 |
| AgO@g-C$_3$N$_4$ | Chemical oxidation | S. aureus | 89% | 275 |
| Fe-$2,5$-thiophenedicarboxylic acid@g-C$_3$N$_4$ | Microwave-heating | E. coli | 100% | 276 |
| Mg$_2$Ti$_3$O$_7$/g-C$_3$N$_4$ | Sol-gel method and calcination | E. coli | 100% | 277 |
| CuWO$_4$/g-C$_3$N$_4$ | Sol–gel method | E. coli | Effective | 278 |
| ZnBi$_2$O$_4$/g-C$_3$N$_4$ | Ultrasound-assisted chemical exfoliation | E. coli | Effective | 279 |
| Cr–ZnO@g-C$_3$N$_4$ | Chemical coprecipitation method | E. coli | Effective | 280 |
[Fig. 6c and e, red arrows indicate protein or intra-cell material leakage and the black arrows indicate bacterial membrane distortion]. In comparison, when SCN–Zn2+@GO was exposed to either 808 nm or 660 nm illumination, the inactivation rate obtained was only 20–66%. Based on the above results, the antibacterial mechanism is proposed in Fig. 6f. The ROS pass through the cell membrane of the bacteria to oxidize intracellular proteins and interfere homeostasis, while hyperthermia weakens the activities of the proteins and reduces adenosine triphosphate synthesis, inactivating E. coli and S. aureus within 10 min. Similarly, novel CoB/g-C3N4 nanosheets were successfully prepared by an electrostatic self-assembly process coupled with calcination.529 The interfacial Co–N bond could act as an e– transport channel by accelerating the e– transfer from g-C3N4 to CoB, as supported by density functional theory (DFT) calculations and indirectly evidenced from antibacterial experiments (Fig. 6g). Consequently, the e– induced O2 reduction process is promoted in CoB/g-C3N4, which boosts the generation of ROS (Fig. 6h). Notably, CoB/g-C3N4 exhibited superior disinfection efficacy of 100% against S. aureus with 125 min under visible light irradiation.

Quantum dots (QDs) are an important low-dimensional semiconductor materials. Because of their high reactivity and strong charge transfer abilities, QDs have been applied in

| Material | Preparation | Bacteria | Effect | Ref. |
|----------|-------------|----------|--------|------|
| ZnBi2O4/g-C3N4 | Thermal polycondensation | B. subtilis | E. coli | 97% | 281 |
| TiO2/Ag/g-C3N4 | Vacuum freeze-drying | E. coli | E. coli | 84% | 282 |
| AgBr/g-C3N4 | Calcination | P. putida | E. coli | 100% | 283 |
| TiO2 nanotubes/Ti/g-C3N4/SnO2 | Dipping and calcination | E. coli | E. coli | 96% | 284 |
| BiOCl/g-C3N4 | Hydrothermal method | E. coli | E. coli | 90% | 285 |
| NiFe2O4/g-C3N4 | Hydrothermal method | A. flavus | E. coli | Effective | 286 |
| Perylene-3,4,9,10-tetracarboxylic diimide/g-C3N4 | In situ | E. coli | S. aureus | Effective | 287 |
| TiO2/g-C3N4 | In situ | E. coli | E. coli | 65% | 288 |
| ZnO/Mn/g-C3N4 | Chemical co-precipitation | E. coli | Effective | 289 |
| ZnTiO2/Si/g-C3N4 | In situ | E. coli | Effective | 290 |
| Ag-ZnO@g-C3N4 | Physical mixing method | E. coli | S. aureus | Effective | 291 |
| Poly(vinyl alcohol)/g-C3N4 | Casting | E. coli | P. aeruginosa | Effective | 292 |
| Polyamine/g-C3N4 | In situ oxidative polymerization methodology | E. coli | S. pneumoniae | Effective | 293 |
| PVA/Starch/Ag@g-TiO2/g-C3N4 | Solution casting | E. coli | S. aureus | Effective | 294 |
| Fe@ZnO@g-C3N4 | Chemical co-precipitation | E. coli | B. subtilis | Effective | 295 |
| g-C3N4-based metal-free | Calcination | E. coli | S. aureus | Effective | 296 |
| Ag,S@g-C3N4 | Sonochemical | B. subtilis | Effective | 297 |
| TiO2 nanofibers/g-C3N4 | Electrospinning-calcination | E. coli | S. aureus | Effective | 298 |
| Ag,PO4/g-C3N4 | Hydrothermal method | E. coli | M. aeruginosa | Effective | 299 |
| Ag,O/g-C3N4 | Chemical deposition method | E. coli | M. aeruginosa | 100% | 300 |
| TiO2/g-C3N4 | Hydrothermal and calcination | E. coli | M. aeruginosa | 100% | 301 |
| Ag,O/g-C3N4 | Physical mixing method | E. coli | Effective | 302 |
| Ag,PO4@g-C3N4 | In situ | Bacteriophage f2 | E. coli | 100% | 303 |
| AgBr@g-C3N4 | Hydrothermal method | E. coli | 100% | 304 |
| TiO2/g-C3N4 | In situ | E. coli | 100% | 305 |
| Porphyrin@g-C3N4 | Hydrothermal method | S. aureus | 100% | 306 |
| Ag/Ag/Ag@g-C3N4/BiVO4 | In situ | E. coli | 63% | 307 |
| ZnO–Cd@g-C3N4 | In situ | Effective | 308 |
| CoB/g-C3N4 | In situ | Effective | 309 |
| RGO/S8@g-C3N4 | In situ | E. coli K-12 | 100% | 310 |
photocatalytic sterilization. Carbon quantum dots (CQDs) were combined with g-C$_3$N$_4$ to enhance charge transfer and store e$^-$ and h$^+$. Tang et al. constructed a CQD/g-C$_3$N$_4$ photocatalyst by impregnation. The addition of CQDs dramatically increased the disinfection performance, which was attributed to the increased ROS levels. The CQD/g-C$_3$N$_4$ nanocomposites exhibit a greatly enhanced bactericidal efficiency under illumination with visible light. In contrast, the CQDs alone showed no catalytic activity against S. aureus under comparable conditions. Hence, the interaction between the CQDs and g-C$_3$N$_4$ plays a significant role in increasing the bacterial inactivation efficiency.

2.4 g-C$_3$N$_4$ heterojunction nanocomposites

Heterojunctions could enable the directional migration of photinduced charges, allowing the charge to be enriched in specific direction, a process that should reduce or even inhibit the recombination of photogenerated carriers. The antimicrobial properties of different g-C$_3$N$_4$ heterojunctions are discussed, including type I and type II heterojunctions, p-n heterojunctions, and Z-scheme heterojunctions. The photocatalytic antibacterial properties of g-C$_3$N$_4$ heterojunction nanocomposites are listed in Table 3.

2.4.1 Type I heterojunction nanocomposites. In general, type I heterojunctions are rarely considered as the optimal choice in photocatalysis because the photogenerated carriers can transfer to the interface with other semiconductors, reducing the redox capacity of the charge carriers. Nevertheless, under visible light irradiation, type I heterojunctions have the unique advantage, i.e. the e$^-$ and h$^+$ can be transferred from one semiconductor to another. If another semiconductor has a wide photoabsorption window, a broad-spectrum-response photocatalyst with minimal charge recombination can be obtained by creating a type I heterojunction (Fig. 7a). Li et al. developed zinc-doped g-C$_3$N$_4$ (g-C$_3$N$_4$–Zn) with Bi$_2$S$_3$ nanorod heterojunctions (g-C$_3$N$_4$–Zn/BiS), using ultrasonication. In contrast to the precursors (g-C$_3$N$_4$–Zn and BiS), effective charge separation at the photocatalyst interface is achieved by adjusting the band gap, the density of the electronic distribution, and the oxygen adsorption capacity of the g-C$_3$N$_4$–Zn/BiS heterojunction. DFT calculations were employed to predict the stable crystal structure and the interface space between CN–Zn and BiS (Fig. 8a). The e$^-$ and h$^+$ were separated effectively by the energy band offset and the interface electric field, hence the g-C$_3$N$_4$–Zn/BiS heterojunction produces abundant ROS and shows excellent photocatalytic efficiency. Near-quantitative bactericidal efficiency towards S. aureus was achieved after only 10 min of NIR irradiation.
irradiation (Fig. 8b). In addition, red P was a novel single-element photocatalyst, and its visible light response range is up to 700 nm. Efficient light harvesting is imperative for photocatalysts, and with this in mind Wang et al. developed a wide-spectral-response g-C_3N_4/red P photocatalyst using ultrasound.\textsuperscript{186–188} Ultrasound was used to obtain nanosheets from bulk g-C_3N_4, and red P particles were anchored to the g-C_3N_4 nanosheets to construct close g-C_3N_4/red P heterojunctions. g-C_3N_4/red P may form a new wide-spectral-responsive photocatalytic system to fully utilize the solar energy. In addition, g-C_3N_4/red P was used as a dual activity center photocatalyst, exhibiting dramatically improved photocatalytic efficiency for sterilization under illumination with visible light. While the g-C_3N_4/red P nanocomposite showed 7 log cfu mL\textsuperscript{-1} bacterial inactivation after 1.3 h, the photocatalytic bacterial inactivation of pure g-C_3N_4 was limited, with <1.5 log cfu mL\textsuperscript{-1} E. coli inactivation after 2 h of illumination.

2.4.2 Type II heterojunction nanocomposites. Type II heterojunctions g-C_3N_4-based nanocomposites have been widely reported as photocatalysts, e.g. Ag_2ZrO_3/g-C_3N_4,\textsuperscript{189} Nb_2O_5/g-C_3N_4 and Bi_2MoO_6/g-C_3N_4.\textsuperscript{190,191} These materials have interlaced band gaps and appropriate VB and CB energies. Staggered heterojunctions are the most efficient type of heterojunctions due to highly efficient charge transfer,\textsuperscript{192–194} and therefore, type II heterojunctions are widely used.\textsuperscript{195} Exposure of a type II heterojunction to visible light results in the transition of an e\textsuperscript{−} from the VB to the CB, generating a corresponding h\textsuperscript{+} in the VB. When the CB of semiconductor A is higher in energy than the CB of semiconductor B, the e\textsuperscript{−} in the CB of semiconductor A is transferred to the CB of semiconductor B. Simultaneously, the h\textsuperscript{+} in the VB of semiconductor B is transferred to the VB of semiconductor A. Finally, they react with O_2 and H_2O in the surrounding media to produce ROS, leading to good antibacterial effects (Fig. 7b). Gao et al. prepared a perylene diimide (PDI)/oxygen-doped g-C_3N_4 nanosheet (PDI/O-g-C_3N_4) nanocomposites using an in situ electrostatic assembly method.\textsuperscript{196} The PDI expanded the visible light range of the material, resulting in abundant photogenerated charge carriers and accumulation of ROS, boosting the oxidative capability. As a consequence, PDI/O-g-C_3N_4 demonstrated strong antibacterial oxidation activity under visible light with 96% of the S. aureus fully inactivated by PDI/O-g-C_3N_4 under 3 h of light irradiation, whereas only 62% of the S. aureus cells were inactivated by the control material. Coincidentally, Bi_2MoO_6 not only intersects the g-C_3N_4 band gap, but also has a very similar band gap energy (~2.7 eV). Consequently, Bi_2MoO_6 combines with g-C_3N_4 to afford neoteric and efficient nanocomposites.\textsuperscript{197,198} As shown in Fig. 9a, Li et al. developed Bi_2MoO_6/g-C_3N_4 heterojunctions using an in situ solvothermal approach.\textsuperscript{199} The results showed that the photocatalyst completely inactivated 2.5 \times 10^7 cfu mL\textsuperscript{-1} E. coli after 3 h light irradiation (Fig. 9b).

2.4.3 Z-scheme heterojunction nanocomposites. Recently, Z-scheme heterojunctions have been widely studied as the structure accelerates the separation of photogenerated carriers. The e\textsuperscript{−} in the VB of semiconductor A transfers to the CB of
semiconductor B, and the remaining $h^+$ and $e^-$ undergo redox reactions with the oxygen and water in the surroundings to generate ROS (Fig. 7c). As expected, Z-scheme heterojunctions exhibit excellent photocatalytic disinfection performance.200–204 MnO$_2$ is an inexpensive, abundant, biocompatible semiconductor that has a similar bandgap to g-C$_3$N$_4$.205–211 Wu et al. successfully constructed a MnO$_2$/g-C$_3$N$_4$–Ti heterojunction using thermal vapor liquid-polymerization and redox methods212 (Fig. 10a). Contact between the g-C$_3$N$_4$ and MnO$_2$ formed a Z-scheme heterojunction. The MnO$_2$/g-C$_3$N$_4$–Ti composite inactivates $S$. aureus and $E$. coli in near-quantitative yields (Fig. 10b and c). In addition, TiO$_2$ is an outstanding photocatalyst that binds with g-C$_3$N$_4$ for form a nanocomposite with high thermal stability.213–219 Li et al. constructed a g-C$_3$N$_4$/TiO$_2$/kaolinite heterojunction using a sol-gel approach combined with self-assembly220 (Fig. 10d). Compared to bulk g-C$_3$N$_4$ or TiO$_2$, the 3D structured g-C$_3$N$_4$/TiO$_2$/kaolinite nanocomposite displayed increased adsorption-photocatalytic sterilization of $S$. aureus under light irradiation. The g-C$_3$N$_4$/TiO$_2$/kaolinite composite inactivated 2.9 log $S$. aureus bacteria after 5 h of illumination, superior to g-C$_3$N$_4$ (1.6 log) and TiO$_2$ (0.8 log) alone (Fig. 10e). In addition, under visible light, the g-C$_3$N$_4$/TiO$_2$/kaolinite nanocomposite exhibits heightened adsorption-photocatalytic degradation of ciprofloxacin, a broad-spectrum antibiotic. The antibacterial efficiency of the g-C$_3$N$_4$/TiO$_2$/kaolinite composite may be attributed to both the improved light utilization and an increase in $e^-/h^+$ transfer and separation efficiency (Fig. 10f). The visible light activated g-C$_3$N$_4$/TiO$_2$/kaolinite composite is a useful material for pollutant decomposition and bacterial elimination.221

2.4.4 Dual-path heterojunction nanocomposites. Generally, the charge migration paths observed in g-C$_3$N$_4$ heterojunctions are mostly type II and Z-scheme heterojunctions, which expedite the fast separation of photogenerated charges and intensify the antibacterial activity of semiconductor materials. Many type II and Z-scheme heterojunction nanocomposites have been shown to inactivate bacteria under irradiation with visible light, including m-Bi$_2$O$_4$/g-C$_3$N$_4$, AgWO$_4$/g-C$_3$N$_4$.222,223 Nevertheless, due to the relatively low redox potentials in type II and Z-scheme heterojunctions, these photocatalysts lack strong redox abilities.224 It is known that $e^-/h^+$ accumulate in the CB of semiconductor A, which has a high reduction potential, and $h^+$ leave the VB of semiconductor B, which has a high oxidation potential. This not only effectively separates the $e^-/h^+$ pairs, but also produces the optimal redox properties. Therefore, the two models of ternary heterojunctions were also studied to further improve the antibacterial performance of photocatalytic heterojunctions. Zeng et al. constructed a ternary BiVO$_4$/Ag/g-C$_3$N$_4$ heterojunction using photo-deposition and hydrothermal methods.225 Based on heterojunction band gap energy level and surface chemistry, a dual Z-scheme photogenerated carrier transfer model was applied to BiVO$_4$/Ag/g-C$_3$N$_4$. Notably, the ternary BiVO$_4$/Ag/g-C$_3$N$_4$ heterojunction markedly strengthened the photocatalytic antibacterial capability, completely inactivating 6.5 log $E$. coli cells after 1 h of light illumination, whereas the binary BiVO$_4$/g-C$_3$N$_4$ heterojunction inactivated only 0.5 log $E$. coli under comparable conditions. The Ag and BiVO$_4$ nanoparticles on the g-C$_3$N$_4$ nanosheets inhibit recombination of the photogenerated carriers, thus promoting ROS generation. Ma et al. developed
Fig. 10  (a) Schematic showing the preparation of MnO$_2$/g-C$_3$N$_4$–Ti. (b and c) The antibacterial effect of MnO$_2$/g-C$_3$N$_4$–Ti irradiated for 20 minutes against *S. aureus* and *E. coli*, respectively. Reproduced from ref. 212 with permission from Elsevier, copyright 2019. (d) Schematic illustration of the preparation of g-C$_3$N$_4$/TiO$_2$/kaolinite. (e) Photocatalytic disinfection efficiency of *S. aureus* for different samples. (f) Schematic diagram of photocatalytic mechanism of the g-C$_3$N$_4$/TiO$_2$/kaolinite. Reproduced from ref. 220 with permission from Elsevier, copyright 2019.
Fig. 11  (a) Preparation of CuS/g-C$_3$N$_4$. (b) Photothermal images following irradiation as a function of concentration and time. (c) In vitro antibacterial activity for *S. aureus* and *E. coli*. Reproduced from ref. 250 with permission from Elsevier, copyright 2020. (d) Formation mechanism of vanadate QDs/g-C$_3$N$_4$. (e) Photocatalytic disinfection efficiency of *Salmonella* with different samples. (f) Photocatalytic disinfection efficiency of *Salmonella* with AgVO$_3$/g-C$_3$N$_4$ at different concentrations. (g) Bacteria colony growth in the presence of AgVO$_3$/g-C$_3$N$_4$ with *Salmonella*. (h) Bacteria colony growth in the presence of AgVO$_3$/g-C$_3$N$_4$ with *Salmonella* at different concentrations. The corresponding thermal images of AgVO$_3$/g-C$_3$N$_4$ following irradiation for (i) 5 min and (j) 10 min. Bacteria colony growth with (k) AgVO$_3$/g-C$_3$N$_4$ and (l) BiVO$_4$/g-C$_3$N$_4$ in the dark. Reproduced from ref. 251 with permission from Elsevier, copyright 2017.
ZnO/Ag@g-C3N4 heterojunction using a solvothermal reaction.\textsuperscript{226} This composite was used to kill E. coli under illumination with visible light. The ZnO/Ag@g-C3N4 composite demonstrated significant visible light sterilization efficiency compared to g-C3N4, Ag@g-C3N4, and ZnO@g-C3N4 materials. Specifically, ZnO/Ag@g-C3N4 inactivated 7.4 log E. coli after 2 h light illumination. However, only 0.49 log and 2.61 log E. coli were inactivated by g-C3N4 and ZnO@g-C3N4. The interface of ZnO improves the sterilization performance by increasing the separation rate of charges because of the SPR effect of Ag and the similar band gap energies of ZnO to g-C3N4.\textsuperscript{227–231}

2.4.5 \textbf{p–n heterojunction nanocomposites.} The construction of p–n type heterojunctions can increase the spectral response range of photocatalytic semiconductors.\textsuperscript{232–234} The p–n type heterojunction needs to form at the interface of the space charge region and these heterojunctions form an internal potential that guides the e\textsuperscript{−} and h\textsuperscript{+} in opposite directions.\textsuperscript{235–239} The e\textsuperscript{−} transfers to the CB of the n-type semiconductor, whereas the h\textsuperscript{+} transfers to the VB of the p-type semiconductor (Fig. 7d). The separation effect of charges in p–n heterojunctions is higher than other heterojunctions leading to superior photocatalytic antibacterial activity.\textsuperscript{240–245} CuS is a p-type semiconductor and is the material of choice for photocatalysis due to its narrow band gap and excellent physiochemical stability.\textsuperscript{246–248} Ding et al. synthesized CuS@g-C3N4 heterojunction using a hydrothermal approach harnessing electrostatic adhesion.\textsuperscript{239} In the CuS@g-C3N4 heterojunction (Fig. 11a), the e\textsuperscript{−} and h\textsuperscript{+} transfer in reverse directions between g-C3N4 and CuS, accelerating the separation of charges, thus producing high levels of ROS and increasing the photocatalytic antibacterial activity. In addition, the CuS@g-C3N4 heterojunction can transform visible light to heat (Fig. 11b). Hence, due to the synergistic influence of the ROS and thermal effects, the CuS@g-C3N4 composite inactivated E. coli and S. aureus bacteria near-quantitatively after 20 min of light irradiation. In contrast, g-C3N4 only inactivated 30% of the E. coli cells and 25% of the S. aureus cells (Fig.11c).

Wang et al. fabricated vanadate (AgVO_3 and BiVO_4) QD@g-C3N4 nanocomposites using urea\textsuperscript{223} (Fig. 11d). Due to the abundant production of ROS by the vanadate QDs and g-C3N4, the vanadate QDs@g-C3N4 composites exhibited high bactericidal efficiency, with 96% inactivation (AgVO_3 QDs@g-C3N4) and 87% inactivation (BiVO_4 QDs@g-C3N4) of Salmonella after only 10 min of light illumination (Fig. 11e and g). As shown in Fig. 11f and h, the photocatalytic disinfection efficiency increases with increasing photocatalyst concentration. Only 22% of Salmonella were killed with a AgVO_3@g-C3N4 composite concentration of 0.5 mg mL\textsuperscript{−1}. However, at the same period, the photocatalytic inactivation of Salmonella increased to 58% when the photocatalyst concentration reach 0.75 mg mL\textsuperscript{−1}. It is apparent from Fig. 11i and j that there is no significant change in temperature during the antibacterial tests. Furthermore, the bacteria grew well on the LB plate, meaning that photocatalyst does not kill the Salmonella (Fig. 11k and l). Considering the simplicity of the synthetic process, the chemical durability and the sterilization results, vanadate QDs@g-C3N4 are ideal photocatalysts for applications in environmental settings.

3. Conclusions and perspectives

Materials based on g-C3N4 are promising photocatalysts with excellent physico-chemical properties and have considerable promise in antibacterial applications. Nevertheless, the antibacterial applications of bulk g-C3N4 are limited by its narrow absorption of visible light and facile recombination of charges. Consequently, a variety of g-C3N4-based nanocomposites have been developed with high superficial areas, improved e\textsuperscript{−}/h\textsuperscript{+} separation efficiencies and expanded visible light absorption ranges, combining to enhance their antibacterial activity. In this review, we highlighted the main strategies used to amplify the photocatalytic efficiency of g-C3N4-based nanocomposites and their antimicrobial properties, including different topologies, noble metal decoration, non-noble metal doping and heterojunction construction. The enhancement mechanisms and synergistic effects of g-C3N4-based nanocomposites was also discussed. Although g-C3N4 is an ideal photocatalyst for the construction of nanocomposites for antibacterial applications, there are still some issues to be solved and opportunities for further research:

(1) The antibacterial mechanism of g-C3N4-based nanocomposites include destroying cell membranes and cell walls, producing endotoxins, causing protein mutations, interfering with protein synthesis and oxidizing organics. However, the role of each process in the antibacterial activity has not yet been clearly defined, suggesting that future research on the antibacterial mechanisms of g-C3N4-based nanocomposites would be meaningful.

(2) Although g-C3N4-based nanocomposites have been extensively studied, the photocatalytic properties are not always predictable, and the performance between g-C3N4 and composites is often found to be additive and not synergistic. Therefore, molecular models that allow better composite design would be useful.

(3) When constructing g-C3N4 heterojunctions, a single heterojunction has many limitations in terms of light absorption and e\textsuperscript{−} separation. Thus, the construction of dual heterojunctions, such as dual Z-type or combined Z-type and type II heterojunctions could enhance the photocatalytic effect of g-C3N4 nanocomposites and is a key topic for future research and development.

(4) The antibacterial efficiency of g-C3N4-based nanocomposite photocatalysts relies largely on ultraviolet and blue light. Extending the range to longer wavelengths would be advantageous.

(5) Most studies were carried at laboratory scales and synthetic strategies for large-scale production are challenging. The development of simple and large-scale green and sustainable synthetic methods that can be automated are required to facilitate commercial applications.

(6) ROS are also able to destroy viruses and therefore further research exploring the antiviral properties of g-C3N4 nanocomposites would be valuable.

Conflicts of interest

There are no conflicts to declare.
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