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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_3N_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_3N_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_3N_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_3N_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_3N_4-based nanocomposites are highlighted. The remaining challenges and future perspectives of antibacterial g-C_3N_4-based nanocomposites are also discussed.

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1. Introduction

Bacterial infections and their transmission pose a considerable threat to human health, usually leading to delayed wound healing and chronic intestinal diseases.[1,2] Furthermore, pathogenic bacteria frequently contaminate water supplies and the soil, resulting in the death of animals and plants through environmental contamination.[3] To address these problems, antibiotics are widely used to kill bacteria, but over-utilization of antibiotics can bring about resistance and secondary contamination.[4–6] Therefore, the development of new strategies

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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[7] and antimicrobial applications.[8] Under sunlight irradiation, semiconductor photocatalysts react with water and oxygen to form reactive oxygen species (ROS), such as hydrogen peroxide (H_2O_2), hydroxyl radicals ($^{\bullet}OH$) and superoxide ($O_2^{\bullet-}$), which are able to inactivate bacteria by oxidizing the phospholipid membrane, proteins and nucleic acids.[9–13] Common photocatalysts include metallic oxides, sulfides, nitrides, and phosphides, and graphene and its derivatives,[14,15] 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.[16] 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-C_3N_4) is easy to prepare and has an appropriate band structure and good biocompatibility,[17] thus showing considerable potential as antibacterial materials.

Similar to the layered structure of graphene, g-C_3N_4 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-C_3N_4 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-C_3N_4 has a two-dimensional flake structure. The adjacent g-C_3N_4 flakes interact weakly with each other *via* van der Waals forces, displaying a layer gap of about 0.33 nm.[18–22] Thus, when such forces between the bulk g-C_3N_4 layers are broken, paper-like g-C_3N_4 nanosheets are obtained.[23–27] From a molecular prospective, C_3N_4 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.[28] Another is a tri-*s*-triazine structurally

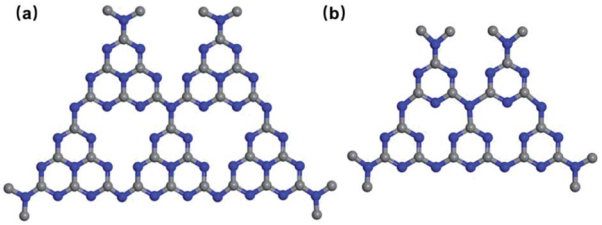

Fig. 1 (a) Tri-*s*-triazine and (b) *s*-triazine structure of g-C_3N_4.

connected to form g-C_3N_4 (Fig. 1b). This more stable tri-*s*-triazine structure is commonly used as the structural unit of g-C_3N_4.[29] These excellent structural features and properties make C_3N_4 a promising photocatalytic material. Since the first study of the photocatalytic activity of g-C_3N_4 by Wang *et al.* in 2009, it has become a prevalent photocatalytic material.[30] Due to the merits of the non-metallic g-C_3N_4 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.[31–35] Specifically, g-C_3N_4 has been used as a catalyst for photocatalytic water reduction and oxidation, contaminant degradation and carbon dioxide reduction.[36–41] For photocatalytic degradation, the photo-produced electrons (e^-) and holes (h^+) can accelerate reduction and oxidation degradation reactions.[42–47] In addition, the e^- and h^+ can react with surrounding H_2O and O_2 to generate ROS such as $^{\bullet}O^{2-}$ and $^{\bullet}OH^-$. The generated ROS can further degrade pollutants, combining to achieve the removal of contaminants.[48–51]

In this review, several tactics for enhancing the antimicrobial efficiency of g-C_3N_4-based nanocomposites are discussed (Fig. 2), including the design of different g-C_3N_4 topologies,[52–55] noble metal decoration,[56–58] non-noble metal doping and heterojunction construction.[59–61] These approaches have been shown to effectively boost the antibacterial activity of g-C_3N_4.[62–67] The enhancement mechanisms and synergistic effects of g-C_3N_4-based nanocomposites is highlighted. Additionally, photocatalytic mechanisms have been elucidated by analyzing the interactions between the nanomaterials and bacteria.

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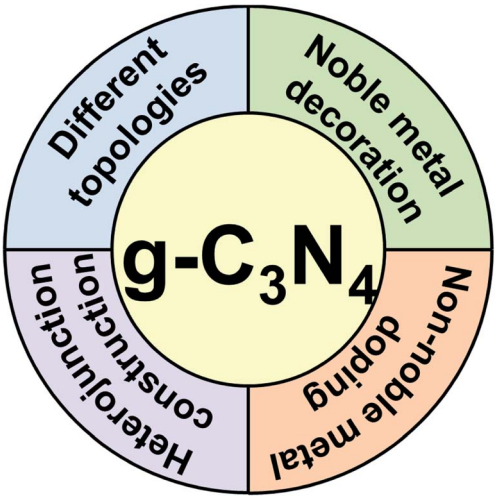

Fig. 2 Schematic illustration of antimicrobial enhancement of g-C_3N_4-nanomaterials.

Lastly, this review concludes by defining future prospects, opportunities and challenges in this exciting field.

2. g-C_3N_4-based materials and their photocatalytic antibacterial

Both the nitrogen and carbon atoms in g-C_3N_4 are sp^2 hybridized to form a conjugated structure with delocalized π-electrons, giving g-C_3N_4 the lowest bandgap compared to other phases of C_3N_4.[68] Compared to other conventional photocatalytic materials, g-C_3N_4 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.[69] The photocatalytic reactions of g-C_3N_4 affect its antibacterial performance. When the energy of the visible light illuminating g-C_3N_4 is larger than the band gap energy of g-C_3N_4, 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-C_3N_4 surface. Alternatively, the e^-/h^+ pairs diffuse or are transported to the g-C_3N_4 interface by an electric field and undergo redox reactions with the surroundings. As shown in Fig. 3, under visible light illumination, g-C_3N_4 produces ROS that can destroy the bacterial membranes, causing cell membrane permeability, structural degradation and ultimately killing the bacterial.[70]

$$\text{g-}C_3N_4 \longrightarrow \text{g-}C_3N_4\ (h^+ + e^-)$$
$$O_2 + e^- \longrightarrow \cdot O_2^-$$
$$H_2O + h^+ \longrightarrow \cdot OH + H^+$$
$$\text{Bacterial membrance} + h^+(\cdot OH, \cdot O_2^-) \longrightarrow \text{products}$$

Fig. 3 Plausible reactions between bacterial and g-C_3N_4-based nanocomposite generated ROS.

2.1 Influence of topology on g-C_3N_4-based antibacterial photocatalysts

The antibacterial activity of g-C_3N_4 is influenced by its topology, in particular, the efficiency of bulk g-C_3N_4 is restricted by its small superficial area and rapid rate of recombination of photogenerated carriers.[71–75] In contrast, mesoporous g-C_3N_4, g-C_3N_4 nanotubes and nanosheets absorb visible light more effectively and provide a larger contact area for reactants because of their larger specific surface areas and a larger number of actives sites.[76,77] In addition, these structures decrease the distance required for the transfer of the charge to the surface of the material, decreasing charge recombination.[78,79] Moreover, due to the quantum size effects, g-C_3N_4 nanosheets are suited to charge transfer and separation processes.[80,81] Therefore, g-C_3N_4 nanosheets and their composite materials show promising photocatalytic antibacterial properties. Li *et al.* developed a self-cleaning antibacterial membrane by simply filtering g-C_3N_4 nanosheets into polyacrylonitrile porous substrates (Fig. 4a), then forming a stable coating by cross-linking polyvinyl alcohol and glutaraldehyde.[82] In contrast to membranes without g-C_3N_4 nanosheets, the membranes containing the g-C_3N_4 nanosheets (0.45 wt%) completely inactivated 1×10^6 cfu mL^{-1} *E. coli* under irradiation with visible light (Fig. 4b and c). The high superficial area of the g-C_3N_4 nanosheets in the membrane provides more active sites that produce ROS for sterilization. Meanwhile, the membranes with g-C_3N_4 nanosheets also showed good permeability to water and degraded dyes. Compared to g-C_3N_4 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 actives sites at their surface, which improves photocatalytic antibacterial performance.[83,84] Xu *et al.* successfully synthesized microtubular nanoporous g-C_3N_4 with a layered structure and nitrogen defects using molecular self-assembly methods.[85] 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-C_3N_4 completely inactivated 5×10^6 cfu mL^{-1} *E. coli* after 4 h of light illumination, compared to only 74% of *E. coli* sterilized by bulk g-C_3N_4. 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.[86] Yang *et al.* successfully fabricated a self-cleaning, antimicrobial and antifouling membrane by integrating mesoporous g-C_3N_4 (MCN) into polyvinylidene fluoride

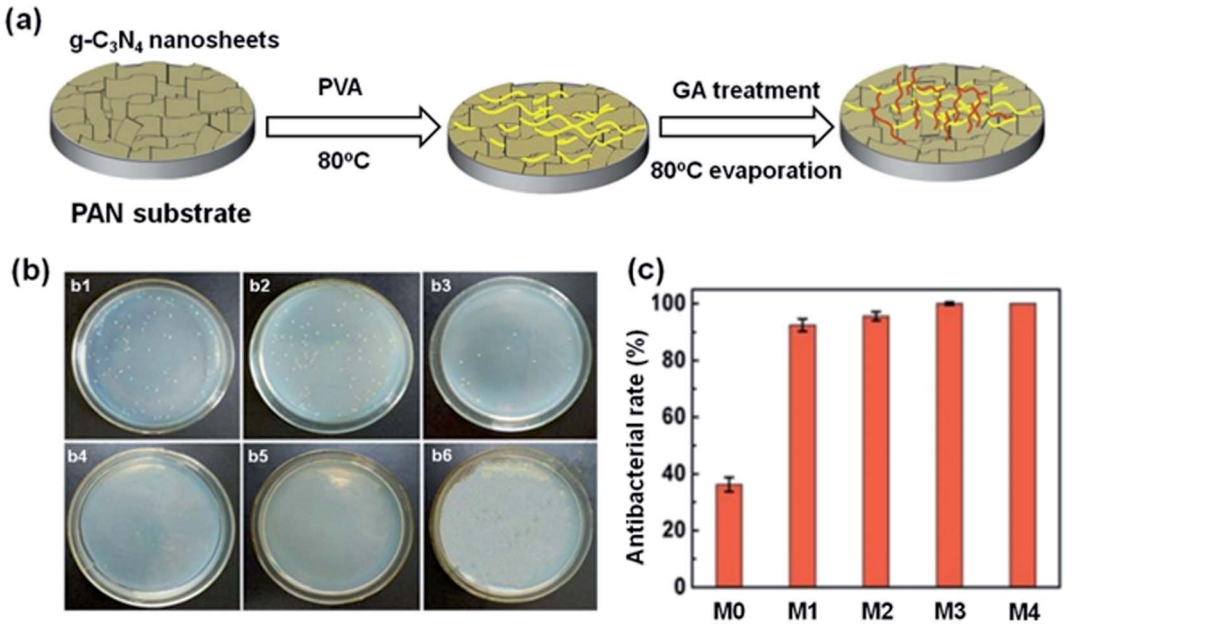

Fig. 4 (a) Preparation of g-C_3N_4 nanosheet-functionalized composite membranes. The concentration of g-C_3N_4 nanosheets in the membrane are 0, 0.15 wt%, 0.3 wt%, 0.45 wt%, 0.6 wt% in M0, M1, M2, M3, M4, respectively. (b) Antimicrobial activities against *E. coli* of (b1) control, (b2) M0, (b3) M1, (b4) M2, (b5) M3, (b6) M4. (c) Antibacterial rate of membranes M0, M1, M2, M3, M4. Reproduced from ref. 82 with permission from Royal Society of Chemistry, copyright 2017.

(PVDF).[87] 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_3N_4 based materials with different topologies

Material	Preparation	Bacteria	Effect	Ref.
g-C_3N_4 nanosheets	Acid etching and ultrasound	*E. coli*	~100%	82
Microtubular nanoporous g-C_3N_4	Molecular self-assembly	*E. coli*	99.2%	85
g-C_3N_4 nanosheets	Freezing and microwave-assisted	*E. coli*	100%	90
Porous g-C_3N_4 nanosheets	Template-free	*E. coli*	100%	91
g-C_3N_4 nanosheets	Bacterial etching	*E. coli*	3.65 log	92
g-C_3N_4 nanosheets	Ultrasound	*E. coli O157:H7*	0.82 log	93
		S. aureus	0.85 log	
g-C_3N_4 nanosheets	Chemical exfoliation	*E. coli K-12*	6.5 log	94
g-C_3N_4 nanosheets	Ultrasound	*E. coli*	99%	95
bare g-C_3N_4	Calcination	*MS2*	100%	96
Mesoporous g-C_3N_4	Immersion-precipitation phase transformation	*E. coli*	3 log	87
Mesoporous g-C_3N_4	Template method	*E. coli K-12*	99%	97
Mesoporous g-C_3N_4	Thermal polymerization and selective dialysis approach	*E. coli*	99%	98
		S. aureus	90%	
Ag_2WO_4/mesoporous g-C_3N_4	Polymerization	*E. coli*	100%	99
GO quantum dots/oxidized nanoporous g-C_3N_4	Self-assembly	*E. coli*	99.6%	100
Nanomesh g-C_3N_4	Template method	*E. coli K-12*	85%	101
$CuInSe_2$:Zn/g-C_3N_4/TiO_2 nanowire	*In situ* growth	*S. aureus*	90%	102
Mesoporous g-C_3N_4	Thermal, polycondensation	*E. coli*	Effective	103
Porous g-C_3N_4	Calcination	*S. aureus*	99%	104
Mesoporous g-C_3N_4	Calcination	*E. coli*	Effective	105
Nanostructured g-C_3N_4	Calcination	*E. coli* O157:H	97.1%	106
		S. aureus	93.7%	
Mesoporous g-C_3N_4	Hydrothermal	*E. coli*	Effective	107
g-C_3N_4 powder	Calcination	*E. coli*	Effective	108
		S. epidermidis		

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-C_3N_4 has a large specific surface area its photocatalytic performance is enhanced, *e.g.* in g-C_3N_4 nanosheets and nanotubes, which have a high density active sites. Furthermore, g-C_3N_4 nanocomposites inhibit e^-/h^+ pair recombination and have high charge transfer efficiency due to enhanced visible light absorption. Hence, discrepant topologies of g-C_3N_4 should have outstanding antibacterial performance and the discrepant topologies of g-C_3N_4-based materials and their corresponding antibacterial properties are summarized in Table 1.

2.2 Noble metal decorated g-C_3N_4 nanocomposites

Another strategy used to increase the antibacterial performance of g-C_3N_4 involves modification with noble metal nanoparticles, including silver and gold nanoparticles.[109,110] Surface Plasmon Resonance (SPR) of nanoparticles enhances antibacterial efficiency, by extending the spectral absorption range and promoting the formation of photogenerated carriers in g-C_3N_4.[111–114] Additionally, noble metal nanoparticles act as electron traps, capturing free e^- and thus inhibiting the

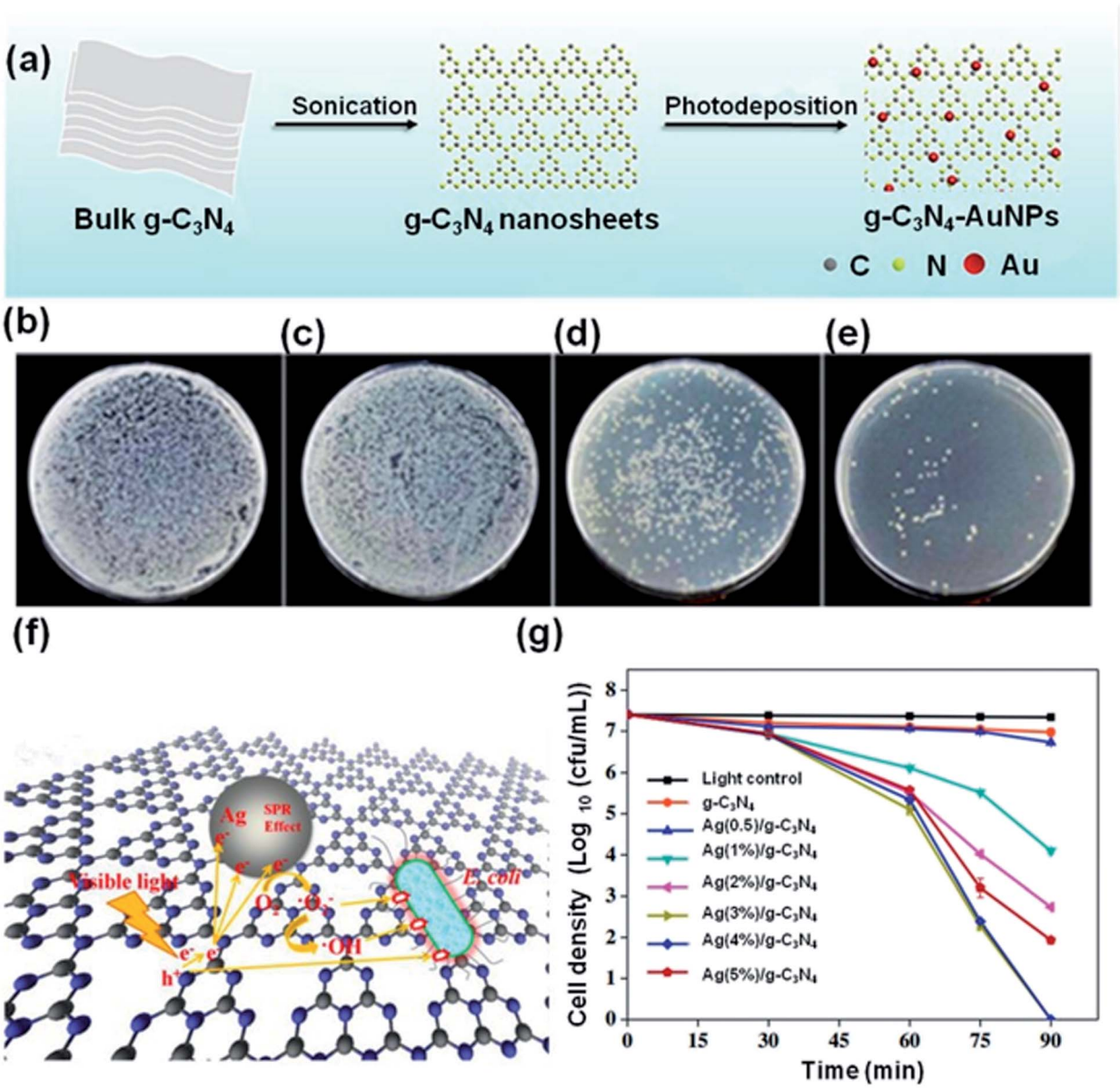

Fig. 5 (a) Preparation of g-C_3N_4-Au nanoparticle nanocomposties. (b) *E. coli* bacteria + control sample. (c) *E. coli* bacteria + g-C_3N_4-1.0% Au. (d) *E. coli* bacteria + g-C_3N_4-1.0% Au + 10 min irradiation. (e) *E. coli* bacteria + g-C_3N_4-1.0% Au + 20 min irradiation. Reproduced from ref. 123 with permission from American Chemical Society, copyright 2019. (f) The mechanism of *E. coli* inactivation in the presence of Ag/g-C_3N_4 under visible light. (g) Disinfection efficiencies of *E. coli* by the samples under visible light irradiation. Reproduced from ref. 119 with permission from Elsevier, copyright 2019.

recombination of photogenerated carriers.[115–118] Ma *et al.* developed Ag/g-C_3N_4 nanocomposites by combining thermal polymerization with photo-assisted reduction.[119] A synergistic antibacterial efficiency was achieved with superior sterilization activity of the Ag/g-C_3N_4 nanocomposite compared to pure g-C_3N_4 (Fig. 5f). Ag(0.3 wt%)/g-C_3N_4 exhibited prominent antibacterial performance and suppressed *E. coli* replication (7.41 log) with only 1.25 h of visible light illumination. In contrast, pure g-C_3N_4 displayed very low inactivation, with only about (0.4 log) *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_3N_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_3N_4 nanosheets.[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).[121,122] As shown in Fig. 5a, Dai *et al.* utilized 5–10 nm sized Au nanoparticles to modify g-C_3N_4 *via* liquid-phase exfoliation of g-C_3N_4 combined with the photodeposition of Au nanoparticles.[123] When a mixture of *E. coli* and the Au/g-C_3N_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_3N_4 nanosheets strikingly improves photocatalytic ROS generation, due to the application of 670 nm light.[124] In general, noble metal/g-C_3N_4 nanocomposites significantly outperform unmodified g-C_3N_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_3N_4 nanocomposites

While g-C_3N_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.[125–129] Thus, g-C_3N_4 nanocomposites derived from inexpensive and abundant elements that are non-toxic would be advantageous.[130–134] In such materials the g-C_3N_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.[135–142] Surface engineering of carbon-based materials has been an effective tool for construction of materials with special functions.[143–149] Advantageously, Lewis basic N-sites on the surface g-C_3N_4 allow strong interactions with Lewis acids, *i.e.* zinc ions, similar to that observed for other materials.[150–157] For example, g-C_3N_4–Zn^{2+}@graphene oxide (SCN–Zn^{2+}@GO) were prepared using chemical vapor deposition (CVD).[158] The bidentate ligand, SCN, may coordinate to the Zn^{2+} ions to form cross-links with GO, and additionally changing the crystal structure of g-C_3N_4 and introducing defect sites (Fig. 6a). The resulting SCN–Zn^{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 *E. coli* and *S. aureus* blank groups possess unbroken topologies, with glossy bacteria membranes and intact intra-cell structures. The membrane structures of both *E. coli* and *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_3N_4 nanocomposites

Main component	Material	Preparation	Bacteria	Effect	Ref.
Noble metal decoration	Ag/g-C_3N_4	Thermal polymerization and photo-assisted reduction	*E. coli*	7.41 log	119
	Ag/g-C_3N_4	Single-pot, microemulsion	*E. coli*	9.95 log	166
	Ag/P/g-C_3N_4	Pyrolysis and green reduction.	*E. coli*	7 log	167
	Ag/polydopamine/g-C_3N_4	Ultrasound and freeze-drying	*E. coli*	Effective	168
	Ag/oxidized porous g-C_3N_4	Photo-assisted, reduction	*S. aureus*	99%	169
	Ag/g-C_3N_4	Biogenic, methodology	*E. coli* *S. aureus* *P. aeruginosa*	Effective	174
	Ag/g-C_3N_4	Calcination	*E. coli* *S. aureus* *B. subtili* *P. aeruginosa*	Effective	175
	Ag/g-C_3N_4	Photo-deposition method	*E. coli* *P. aeruginosa*	Effective	177
	Au/g-C_3N_4	Liquid-phase, exfoliation and photodeposition	*E. coli*	Effective	123
	Au/g-C_3N_4	Deposition–precipitation	*E. coli* *S. aureus*	82% 79%	170
	Au/g-C_3N_4	Calcination	*E. coli*	99%	176
Non-noble metal doping	g-C_3N_4-Zn^{2+}@graphene	Chemical vapor deposition and ultrasonic dispersion	*S. aureus*	99%	158
	CQDs/g-C_3N_4	Impregnation	*S. aureus*	7 log	165
	Fullerene/g-C_3N_4	Hydrothermal method	*E. coli O157:H7*	86%	171
	S-CQD/hollow tubular g-C_3N_4	Self-assembly and ultrasound	*E. coli*	6.88 log	172
	Ag/P/Co/S/g-C_3N_4	Calcination	*E. coli*	7 log	173

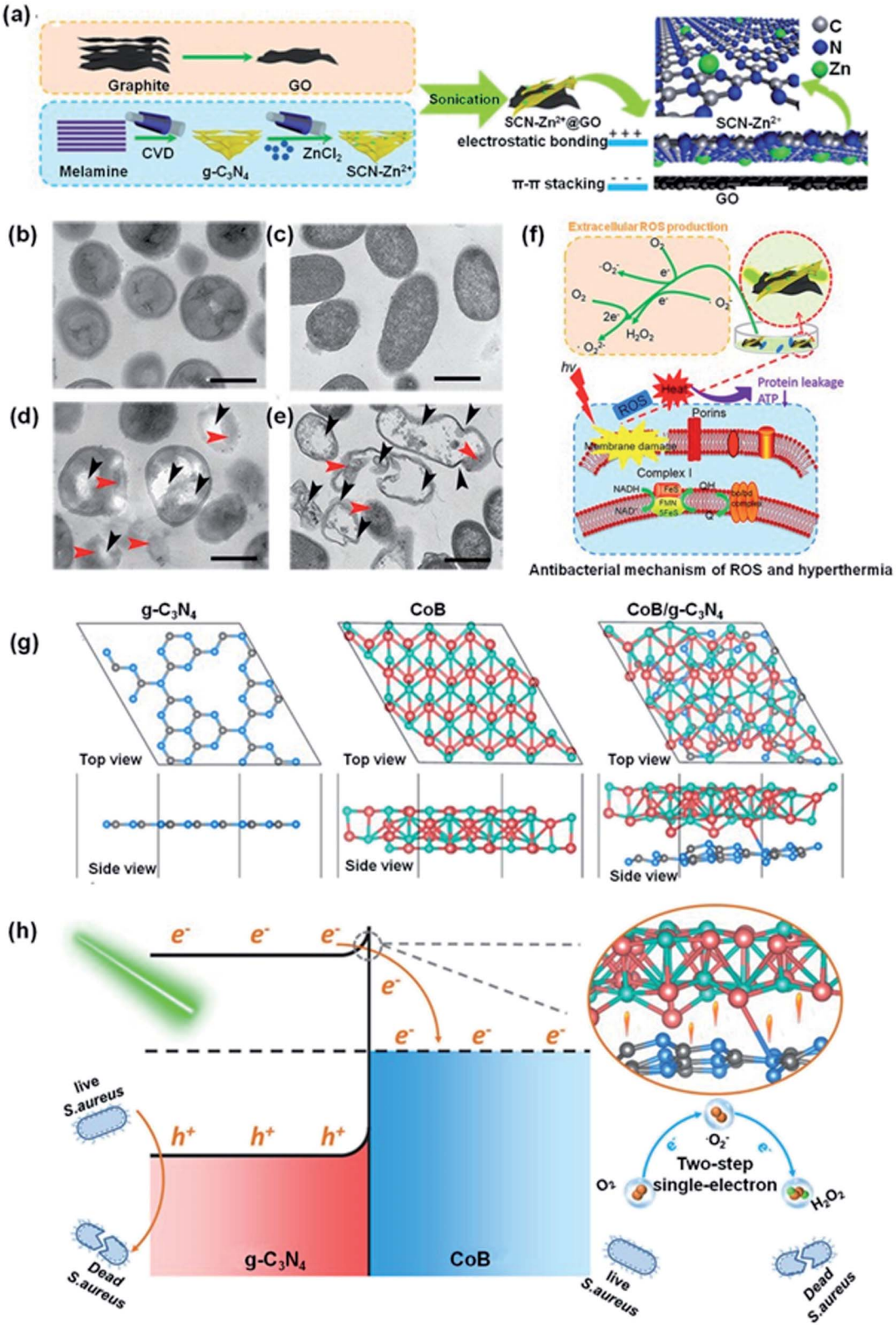

Fig. 6 (a) Preparation of SCN–Zn^{2+}@GO. TEM topology of *S. aureus* (b) and *E. coli* (c) as control, (d) and (e) following treatment with SCN–Zn^{2+}@GO 20% after 10 min irradiation with visible light (the red arrows indicate protein leakage and the dark arrows indicate rupture or ruffling of the bacterial membrane). (f) Antibacterial mechanism of SCN–Zn^{2+}@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-C_3N_4 (001) surface, CoB-(010) surface and CoB/g-C_3N_4 after geometry optimization. (h) The mechanism of *S. aureus* bacteria inactivation in the presence of CoB/g-C_3N_4 under visible light. Reproduced from ref. 159 with permission from the American Chemical Society, copyright 2019.

Table 3 Antibacterial properties of g-C_3N_4 heterojunction nanocomposites

Material	Preparation	Bacteria	Effect	Ref.
Bi_2S_3/g-C_3N_4	Ultrasound	*E. coli* *S. aureus*	99.6% 99.2%	185
Red P/g-C_3N_4	Sonochemical	*E. coli K-12*	7 log	186
Perylene diimide/oxygen-doped g-C_3N_4	*In situ* electrostatic assembling	*S. aureus*	99.6%	196
Bi_2MoO_6/g-C_3N_4	*In situ* solvothermal	*E. coli*	100%	199
MnO_2/g-C_3N_4	Thermal vapor liquid-polymerization and redox	*E. coli* *S. aureus*	99.96% 99.26%	212
TiO_2/kaolinite/g-C_3N_4	Sol–gel method	*S. aureus*	2.9 log	220
Ag/AgBr/g-C_3N_4/nitrogen-doped graphene aerogel	Hydrothermal and freeze-drying	*E. coli* *S. aureus*	~6 log ~1.2 log	252
Ag/AgBr/g-C_3N_4	*In situ* deposition–precipitation	*E .coli*	7.9 log	253
Ag_2WO_4/g-C_3N_4	Ultrasound	*E. coli*	90%	222
Ag_2PO_4/g-C_3N_4	Co-precipitation and thermal pyrolysis	*E. coli* *S. aureus*	Effective	254
Ni_2P/g-C_3N_4	*In situ* anchoring and hydrothermal	*E. coli K-12*	7 log	255
m-Bi_2O_4/g-C_3N	Hydrothermal	*E. coli K-12*	6 log	223
Vanadium modified g-C_3N_4/TiO_2	Calcination and ultrasonic	*E. coli* *S. aureus*	Effective	256
$BiVO_4$/Ag/g-C_3N_4	Photodeposition and hydrothermal	*E. coli*	6.5 log	225
Ag/ZnO/g-C_3N_4	Thermal polymerization and solvothermal	*E. coli*	7.4 log	226
Ag/ZnO/g-C_3N_4	Thermal polymerization and solvothermal	*E. coli*	6.19 log	257
Ag_2WO_4/Ag/g-C_3N_4	Hydrothermal and situ reductive	*E. coli*	3.05 log	258
Bi_2MoO_6–Ag/g-C_3N_4	Hydrothermal method	*E. coli* *S. aureus*	Effective	259
α-Fe_2O_3/CeO_2/g-C_3N_4	Hydrothermal method	*E. coli* *S. aureus*	Effective	260
CuS/g-C_3N_4	Electrostatic adsorption	*E. coli* *S. aureus*	99% 98%	250
Vanadate QDs/g-C_3N_4	Sol–gel method	*Salmonella H9812*	96%	251
BiOI/g-C_3N_4	*In situ* generation	*E. coli* *S. aureus*	96% 98%	261
Cu_2O/g-C_3N_4	Chemical precipitation	*E. coli*	7 log	262
Cu_2O/g-C_3N_4	Hydrothermal method	*E. coli* *S. aureus*	Effective	263
TiO_2 nanofibers/Ag/g-C_3N_4	Ultrasound	*E. coli* *S. aureus*	99% 83%	264
Ag/AgCl/g-C_3N_4	*In situ* implanting and anchoring	Tetracycline-resistant bacteria	100%	265
γ-Fe_2O_3/Ag/AgCl/g-C_3N_4	Solvothermal and photodeposition	*E. coli*	5.59 log	266
RGO/CA/g-C_3N_4	Ultrasonification	*E. coli*	6.5 log	267
TiO_2/CuBA/g-C_3N_4	Ultrasound	*E. coli* *S. aureus*	Effective	268
Ag_2ZrO_3/g-C_3N_4	Co-precipitation	*E. coli* *B. subtilis*	97% 99%	189
AgBr/g-C_3N_4	Adsorption deposition	*E. coli*	6.5 log	269
$BiFeO_3$/Cu_2O/g-C_3N_4	Hydrothermally and ultrasonic	*E. coli* *S. aureus*	Effective	270
ZnO/g-C_3N_4/cellulose	Ultrasonic irradiation	*E. coli* *S. aureus*	Effective	271
CdS/g-C_3N_4	Sonochemical	*E. coli* *S. aureus*	Effective	272
GO/g-C_3N_4	Sonication	*E. coli*	97.9%	70
AgCl/CNTs/g-C_3N_4	Deposition–precipitation	*E. coli*	Effective	273
MoO_{3-x}/g-C_3N_4	Hydrothermal	*E. coli*	100%	274
AgO/g-C_3N_4	Chemical oxidation	*S. aureus*	89%	275
Fe-2,5-thiophenedicarboxylic acid/g-C_3N_4	Microwave-heating	*E. coli*	100%	276
$Mg_{1.2}Ti_{1.8}O_5$/g-C_3N_4	Sol–gel method and calcination	*E. coli*	100%	277
$CuWO_4$/g-C_3N_4	Sol–gel method	*E. coli* *S. aureus*	Effective	278
$ZnBi_2O_4$/g-C_3N_4	Ultrasound-assisted chemical exfoliation	*E. coli* *S. aureus*	Effective	279
Cr–ZnO/g-C_3N_4	Chemical coprecipitation method	*E. coli* *S. aureus*	Effective	280

Table 3 (*Contd.*)

Material	Preparation	Bacteria	Effect	Ref.
		B. subtilis		
$ZnBi_2O_4$/g-C_3N_4	Thermal polycondensation	*E. coli*	97%	281
TiO_2/Ag/g-C_3N_4	Vacuum freeze-drying	*E. coli*	84%	282
AgBr/g-C_3N_4	Calcination	*P. putida*	100%	283
TiO_2 nanotubes/Ti/g-C_3N_4/SnO_2	Dipping and calcination	*E. coli*	Effective	284
BiOCl/g-C_3N_4	Hydrothermal method	*E. coli*	96%	285
$NiFe_2O_4$/g-C_3N_4	Hydrothermal method	*A. flavus*	90%	286
Perylene-3,4,9,10-tetracarboxylic diimide/g-C_3N_4	*In situ*	*E. coli* *S. aureus*	Effective	287
TiO_2/g-C_3N_4	*In situ*	*E. coli*	65%	288
ZnO/Mn/g-C_3N_4	Chemical co-precipitation	*E. coli* *S. aureus*	Effective	289
$ZnTiO_2$/S/g-C_3N_4	*In situ*	*E. coli* *S. aureus*	Effective	290
Ag–ZnO@g-C_3N_4	Physical mixing method	*E. coli* *S. aureus* *B. subtilis*	Effective	291
Poly(vinyl alcohol)/g-C_3N_4	Casting	*P. aeruginosa*	Effective	292
Polyaniline/g-C_3N_4	*In situ* oxidative polymerization methodology	*E. coli* *S. pneumoniae*	Effective	293
PVA/Starch/Ag@TiO_2/g-C_3N_4	Solution casting	*E. coli* *S. aureus*	Effective	294
Fe@ZnO/g-C_3N_4	Chemical co-precipitation	*E. coli* *S. aureus* *B. subtilis* *S. salivarius*	Effective	295
g-C_3N_4-based metal-free	Calcination	*E. coli* *B. subtilis*	Effective	296
Ag_2S/g-C_3N_4	Sonochemical	*E. coli* *S. aureus* *B. subtilis* *S. salivarius*	Effective	297
TiO_2 nanofibers/g-C_3N_4	Electrospinning-calcination	*E. coli* *S. aureus*	100%	298
Ag_3PO_4/g-C_3N_4	Hydrothermal method	*E. coli*	Effective	299
Ag_2O/g-C_3N_4	Chemical deposition method	*M. aeruginosa*	99%	300
TiO_2/g-C_3N_4	Hydrothermal and calcination	*E. coli*	100%	301
Ag_2O/g-C_3N_4	Physical mixing method	*M. aeruginosa*	100%	302
AgO/g-C_3N_4	*In situ*	*E. coli*	Effective	303
Ag_3PO_4/g-C_3N_4	Hydrothermal method	*Bacteriophage f2*	100%	304
AgBr/g-C_3N_4	*In situ*	*E. coli*	100%	305
TiO_2/g-C_3N_4	Hydrothermal	*E. coli*	100%	306
Porphyrin/g-C_3N_4	*In situ*	*S. aureus*	63%	307
Ag/Ag/Ag/g-C_3N_4/$BiVO_4$	*In situ*	*E. coli*	100%	308
ZnO–Cd/g-C_3N_4	*In situ*	*E. coli* *S. aureus*	Effective	309
RGO/S_8/g-C_3N_4	*In situ*	*E. coli K-12*	100%	310

(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–Zn^{2+}@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, inactiving *E. coli* and *S. aureus* within 10 min. Similarly, novel CoB/g-C_3N_4 nanosheets were successfully prepared by an electrostatic self-assembly process coupled with calcination.[159] The interfacial Co–N bond could act as an e^- transport channel by accelerating the e^- transfer from g-C_3N_4 to CoB, as supported by density functional theory (DFT) calculations and indirectly evidenced from antibacterial experiments (Fig. 6g). Consequently, the e^- induced O_2 reduction process is promoted in CoB/g-C_3N_4, which boosts the generation of ROS (Fig. 6h). Notably, CoB/g-C_3N_4 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

photocatalytic sterilization.[160] Carbon quantum dots (CQDs) were combined with g-C_3N_4 to enhance charge transfer and store e^-.[161–164] Tang *et al.* constructed a CQD/g-C_3N_4 photocatalyst by impregnation.[165] The addition of CQDs dramatically increased the disinfection performance, which was attributed to the increased ROS levels. The CQD/g-C_3N_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_3N_4 plays a significant role in increasing the bacterial inactivation efficiency.

2.4 g-C_3N_4 heterojunction nanocomposites

Heterojunctions could enable the directional migration of photoinduced charges, allowing the charge to be enriched in specific direction, a process that should recue or even inhibit the recombination of photogenerated carriers.[178,179] The antimicrobial properties of different g-C_3N_4 heterojunctions are discussed, including type I and type II heterojunctions, p–n heterojunctions, and Z-scheme heterojunctions.[180–184] The photocatalytic antibacterial properties of g-C_3N_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_3N_4 (g-C_3N_4–Zn) with Bi_2S_3 nanorod heterojunctions (g-C_3N_4–Zn/BiS), using ultrasonication.[185] In contrast to the precursors (g-C_3N_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_3N_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_3N_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

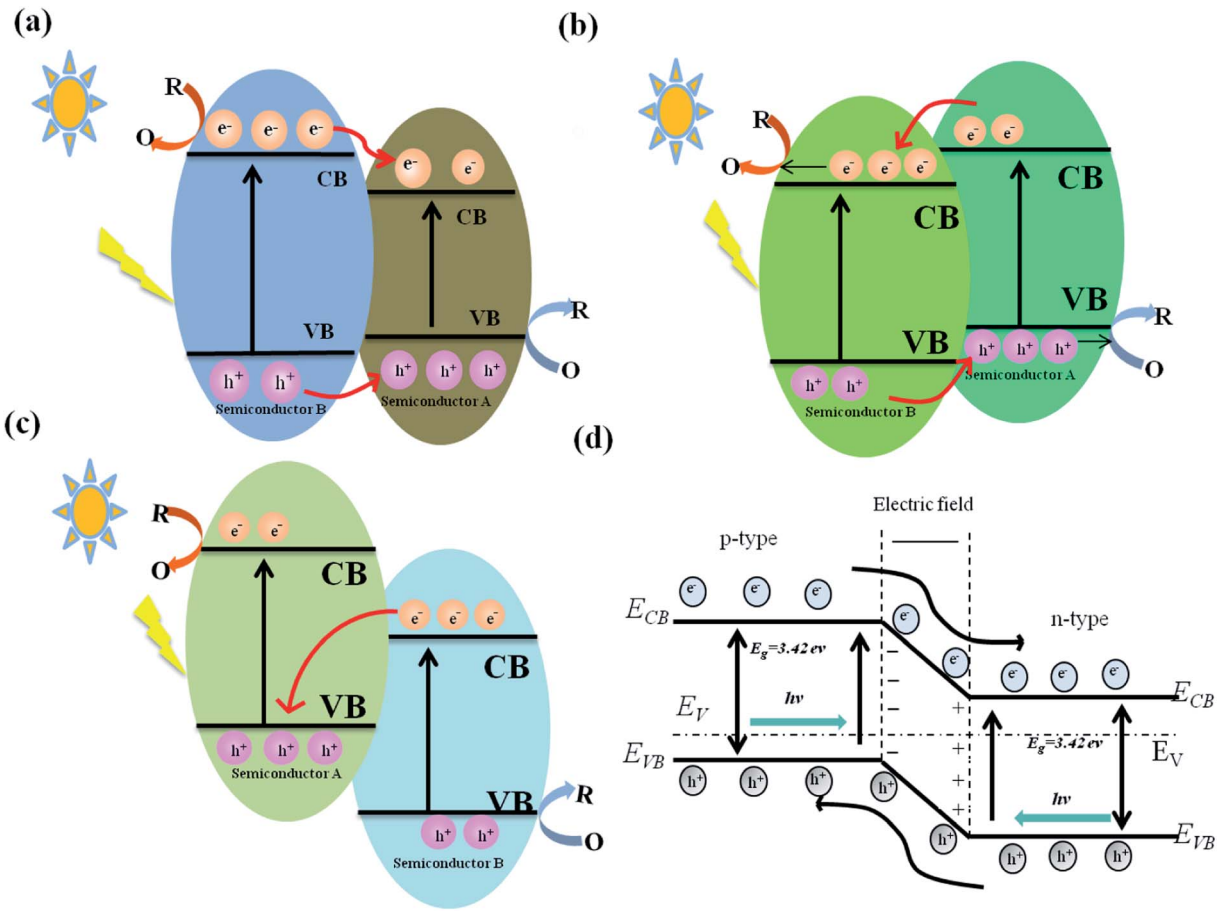

Fig. 7 Various types of heterojunctions. (a) Type I heterojunction model. (b) Type II heterojunction model. (c) Z-type heterojunction model. (d) p–n heterojunction model.

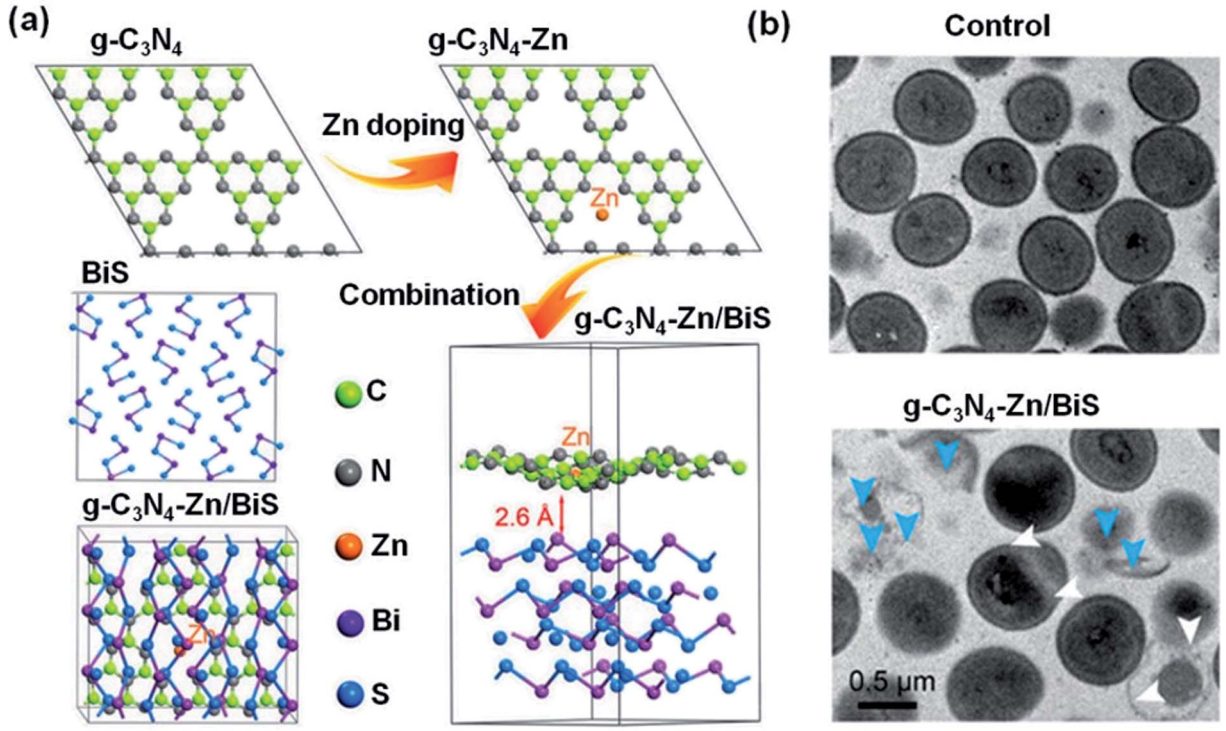

Fig. 8 (a) Structural models of g-C_3N_4, g-C_3N_4–Zn, BiS, and g-C_3N_4–Zn/BiS after geometry optimization. (b) TEM topology of *S. aureus* after treatment with control or g-C_3N_4–Zn/BiS after 10 min irradiation. The white arrows indicate twisted and broken cell membranes and the blue arrows point to intracellular matrix outflow. Reproduced from ref. 185 with permission from WILEY-VCH, copyright 2019.

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.[186–188] Ultrasonication 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^{-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^{-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,[189] Nb_2O_5/g-C_3N_4 and Bi_2MoO_6/g-C_3N_4.[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,[192–194] and therefore, type II heterojunctions are widely used.[195] Exposure of a type II heterojunction to visible light results in the transition of an e^- from the VB to the CB, generating a corresponding h^+ in the VB. When the CB of semiconductor A is higher in energy than the CB of semiconductor B, the e^- in the CB of semiconductor A is transferred to the CB of semiconductor B. Simultaneously, the h^+ 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.[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.[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.[199] The results showed that the photocatalyst completely inactivated 2.5×10^7 cfu mL^{-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^- in the VB of semiconductor A transfers to the CB of

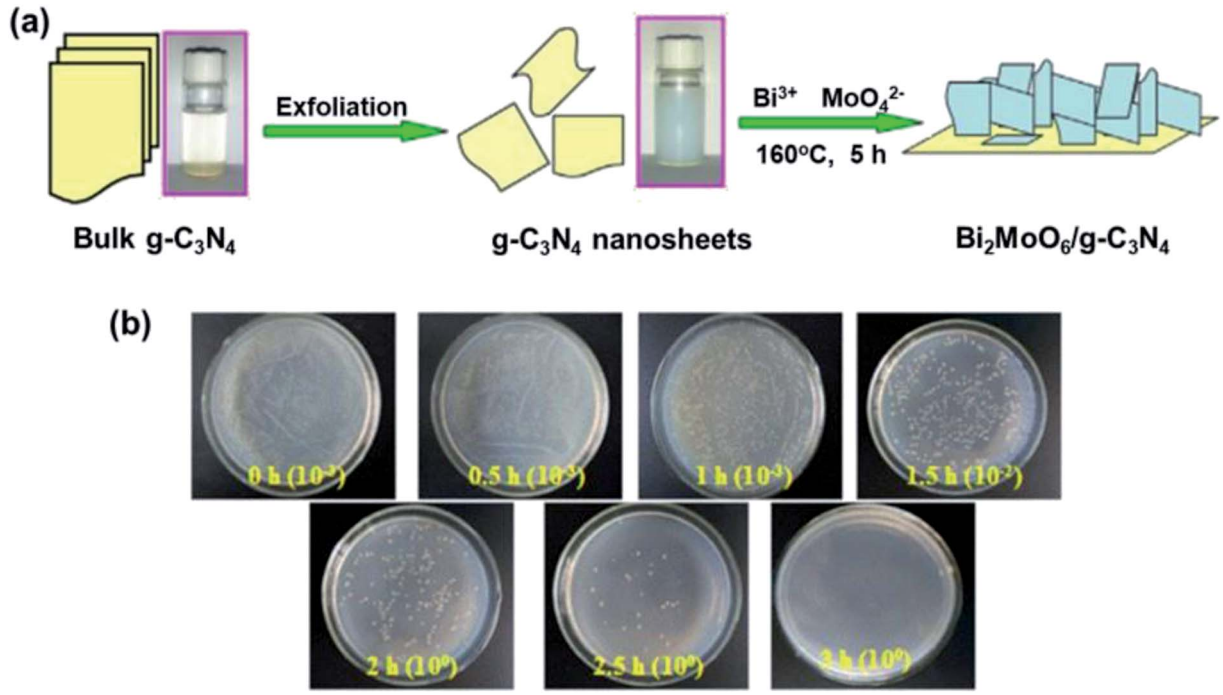

Fig. 9 (a) Preparation of the Bi_2MoO_6/g-C_3N_4 heterojunction. (b) *E. coli* re-cultured after treatment with 20% Bi_2MoO_6/g-C_3N_4 as a function of time. Reproduced from ref. 199 with permission from Elsevier, copyright 2016.

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_3N_4.[205–211] Wu *et al.* successfully constructed a MnO_2/g-C_3N_4–Ti heterojunction using thermal vapor liquid-polymerization and redox methods[212] (Fig. 10a). Contact between the g-C_3N_4 and MnO_2 formed a Z-scheme heterojunction. The MnO_2/g-C_3N_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_3N_4 for form a nanocomposite with high thermal stability.[213–219] Li *et al.* constructed a g-C_3N_4/TiO_2/kaolinite heterojunction using a sol–gel approach combined with self-assembly[220] (Fig. 10d). Compared to bulk g-C_3N_4 or TiO_2, the 3D structured g-C_3N_4/TiO_2/kaolinite nanocomposite displayed increased adsorption-photocatalytic sterilization of *S. aureus* under light irradiation. The g-C_3N_4/TiO_2/kaolinite composite inactivated 2.9 log *S. aureus* bacteria after 5 h of illumination, superior to g-C_3N_4 (1.6 log) and TiO_2 (0.8 log) alone (Fig. 10e). In addition, under visible light, the g-C_3N_4/TiO_2/kaolinite nanocomposite exhibits heightened adsorption-photocatalytic degradation of ciprofloxacin, a broad-spectrum antibiotic. The antibacterial efficiency of the g-C_3N_4/TiO_2/kaolinite composite may be attributed to both the improved light utilization and an increase in e^- transfer and separation efficiency (Fig. 10f). The visible light activated g-C_3N_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_3N_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_2O_4/g-C_3N_4, $AgWO_4$/g-C_3N_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^- 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_3N_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_3N_4. Notably, the ternary $BiVO_4$/Ag/g-C_3N_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_3N_4 heterojunction inactivated only 0.5 log *E. coli* under comparable conditions. The Ag and $BiVO_4$ nanoparticles on the g-C_3N_4 nanosheets inhibit recombination of the photogenerated carriers, thus promoting ROS generation. Ma *et al.* developed

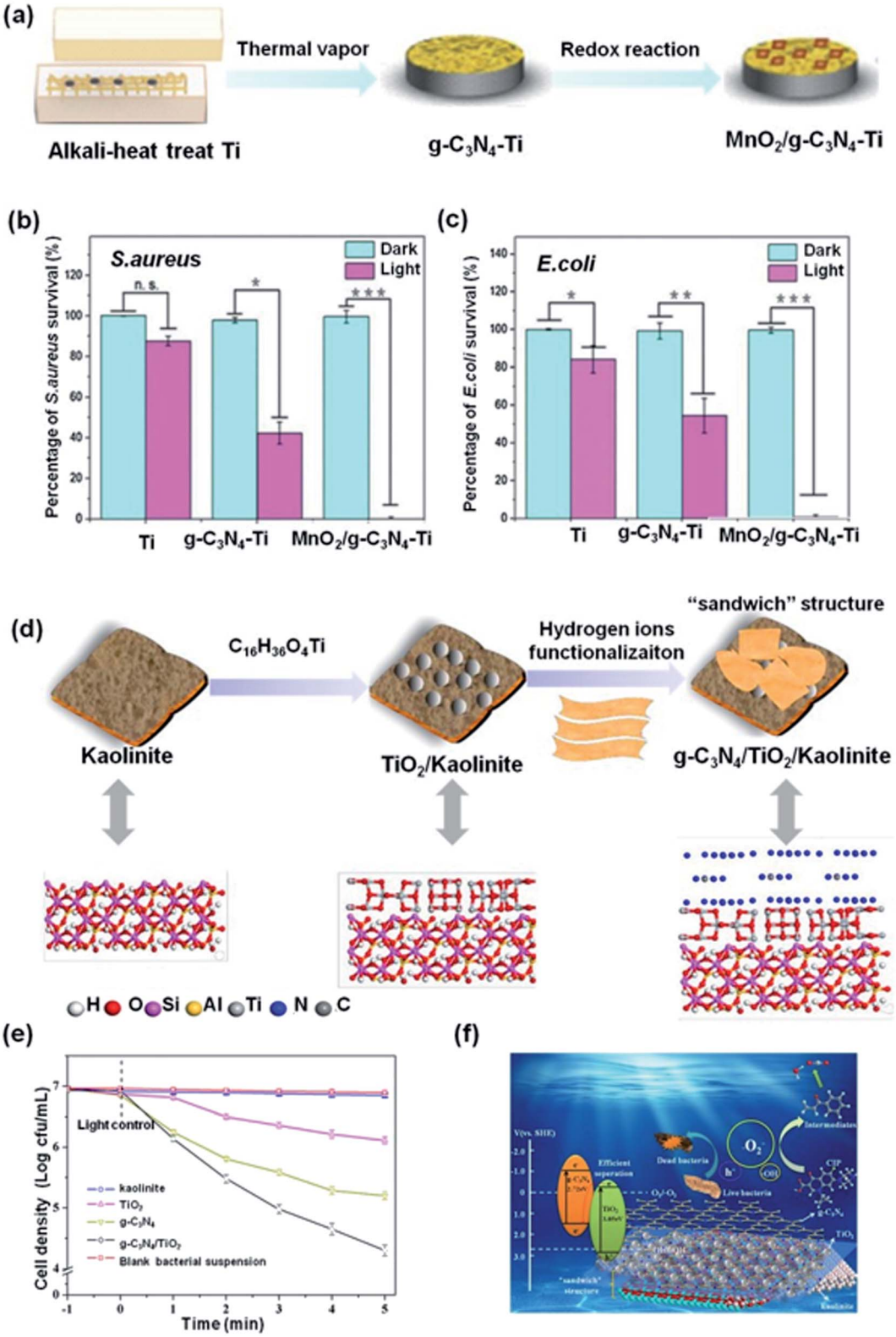

Fig. 10 (a) Schematic showing the preparation of MnO_2/g-C_3N_4–Ti. (b and c) The antibacterial effect of MnO_2/g-C_3N_4–Ti irradiated for 20 minutes against *S. aureus* and *E. coli*, respectively. Reproduced from ref. 212 with permission from Elsevier, copyright 2019. (d) Schematic illustration of the preparation of g-C_3N_4/TiO_2/kaolinite. (e) Photocatalytic disinfection efficiency of *S. aureus* for different samples. (f) Schematic diagram of photocatalytic mechanism of the g-C_3N_4/TiO_2/kaolinite. Reproduced from ref. 220 with permission from Elsevier, copyright 2019.

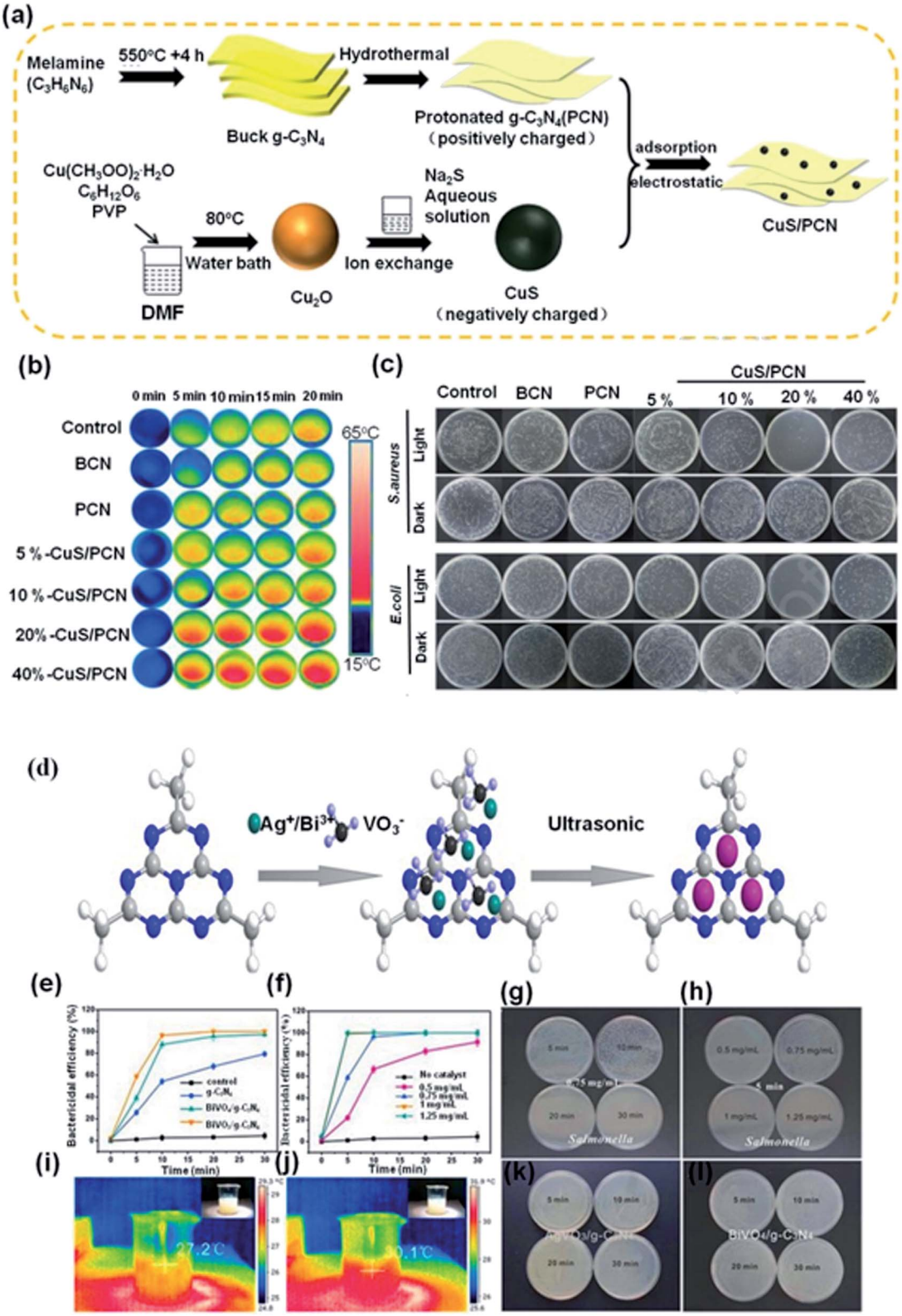

Fig. 11 (a) Preparation of CuS/g-C_3N_4. (b) Photothermal images following irradiation as a function of concentration and time. (c) *In vitro* antibacterial activity for *S. aureus* and *E. coli*. Reproduced from ref. 250 with permission from Elsevier, copyright 2020. (d) Formation mechanism of vanadate QDs/g-C_3N_4. (e) Photocatalytic disinfection efficiency of *Salmonella* with different samples. (f) Photocatalytic disinfection efficiency of *Salmonella* with $AgVO_3$/g-C_3N_4 at different concentrations. (g) Bacteria colony growth in the presence of $AgVO_3$/g-C_3N_4 with *Salmonella*. (h) Bacteria colony growth in the presence of $AgVO_3$/g-C_3N_4 with *Salmonella* at different concentrations. The corresponding thermal images of $AgVO_3$/g-C_3N_4 following irradiation for (i) 5 min and (j) 10 min. Bacteria colony growth with (k) $AgVO_3$/g-C_3N_4 and (l) $BiVO_4$/g-C3N4 in the dark. Reproduced from ref. 251 with permission from Elsevier, copyright 2017.

$ZnO/Ag/g\text{-}C_3N_4$ heterojunction using a solvothermal reaction.[226] This composite was used to kill *E. coli* under illumination with visible light. The $ZnO/Ag/g\text{-}C_3N_4$ composite demonstrated significant visible light sterilization efficiency compared to $g\text{-}C_3N_4$, $Ag/g\text{-}C_3N_4$ and $ZnO/g\text{-}C_3N_4$ materials. Specifically, $ZnO/Ag/g\text{-}C_3N_4$ 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 $g\text{-}C_3N_4$ and $ZnO/g\text{-}C_3N_4$. 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 $g\text{-}C_3N_4$.[227–231]

2.4.5 p–n heterojunction nanocomposites. The construction of p–n type heterojunctions can increase the spectral response range of photocatalytic semiconductors.[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^- and h^+ in opposite directions.[235–239] The e^- transfers to the CB of the n-type semiconductor, whereas the h^+ 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.[240–245] CuS is a p-type semiconductor and is the material of choice for photocatalysis due to its narrow band gap and excellent physicochemical stability.[246–249] Ding *et al.* synthesized $CuS/g\text{-}C_3N_4$ heterojunction using a hydrothermal approach harnessing electrostatic adhesion.[250] In the $CuS/g\text{-}C_3N_4$ heterojunction (Fig. 11a), the e^- and h^+ transfer in reverse directions between $g\text{-}C_3N_4$ and CuS, accelerating the separation of charges, thus producing high levels of ROS and increasing the photocatalytic antibacterial activity. In addition, the $CuS/g\text{-}C_3N_4$ heterojunction can transform visible light to heat (Fig. 11b). Hence, due to the synergistic influence of the ROS and thermal effects, the $CuS/g\text{-}C_3N_4$ composite inactivated *E. coli* and *S. aureus* bacteria near-quantitatively after 20 min of light irradiation. In contrast, $g\text{-}C_3N_4$ 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/$g\text{-}C_3N_4$ nanocomposites using urea[251] (Fig. 11d). Due to the abundant production of ROS by the vanadate QDs and $g\text{-}C_3N_4$, the vanadate QDs/$g\text{-}C_3N_4$ composites exhibited high bactericidal efficiency, with 96% inactivation ($AgVO_3$ QDs/$g\text{-}C_3N_4$) and 87% inactivation ($BiVO_4$ QDs/$g\text{-}C_3N_4$) 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 $AgVO_3/g\text{-}C_3N_4$ composite concentration of 0.5 mg mL^{-1}. However, at the same period, the photocatalytic inactivation of *Salmonella* increased to 58% when the photocatalyst concentration reach 0.75 mg mL^{-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/$g\text{-}C_3N_4$ are ideal photocatalysts for applications in environmental settings.

3. Conclusions and perspectives

Materials based on $g\text{-}C_3N_4$ are promising photocatalysts with excellent physico-chemical properties and have considerable promise in antibacterial applications. Nevertheless, the antibacterial applications of bulk $g\text{-}C_3N_4$ are limited by its narrow absorption of visible light and facile recombination of charges. Consequently, a variety of $g\text{-}C_3N_4$-based nanocomposites have been developed with high superficial areas, improved e^-/h^+ 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 $g\text{-}C_3N_4$-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 $g\text{-}C_3N_4$-based nanocomposites was also discussed. Although $g\text{-}C_3N_4$ 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 $g\text{-}C_3N_4$-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 $g\text{-}C_3N_4$-based nanocomposites would be meaningful.

(2) Although $g\text{-}C_3N_4$-based nanocomposites have been extensively studied, the photocatalytic properties are not always predictable, and the performance between $g\text{-}C_3N_4$ and co-composites is often found to be additive and not synergistic. Therefore, molecular models that allow better composite design would be useful.

(3) When constructing $g\text{-}C_3N_4$ heterojunctions, a single heterojunction has many limitations in terms of light absorption and e^- 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 $g\text{-}C_3N_4$ nanocomposites and is a key topic for future research and development.

(4) The antibacterial efficiency of $g\text{-}C_3N_4$-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 $g\text{-}C_3N_4$ nanocomposites would be valuable.

Conflicts of interest

There are no conflicts to declare.

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