Ag$_2$S nanoparticles anchored on P-doped g-C$_3$N$_4$: a novel 0D/2D p-n 2 heterojunction for superior photocatalytic inactivation of 3 multidrug-resistant $E.~coli$

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Abstract

Photocatalytic inactivation has been proved to be an effective strategy to eliminate pathogenic bacteria in water. Herein, a novel 0D/2D p-n heterojunction of Ag$_2$S-anchored P-doped g-C$_3$N$_4$ (Ag$_2$S/PCN) were constructed by a simple two-step process coupling one-pot calcination and ultrasonic-assisted synthesis. The photocatalytic performance of as-prepared Ag$_2$S/PCN composites was investigated by inactivating multidrug-resistant $E.~coli$ under visible light irradiation. The results indicated that Ag$_2$S/PCN-5 possessed outstanding photocatalytic inactivation activity and superior stability, which could completely inactivate $7.0~\log$ $E.~coli$ cells within 60 min. The enhanced photocatalytic activity of Ag$_2$S/PCN-5 was mainly attributed to the elevated visible-light response and improved production and transfer of photoexcited charges. In addition, the free radicals trapping experiments results revealed that $h^+$ and $\cdot$O$_2^-$ were predominantly responsible for the efficient inactivation activity. Finally, according to the 0D/2D structure and energy band configuration analysis, the enhanced p-n type heterojunction photocatalytic inactivation mechanism of Ag$_2$S/PCN was discussed in detail.

1. Introduction

The frequent emergence of multidrug-resistant pathogenic bacteria, especially existed in hospital wastewater, posed a severe epidemic threat to human health [1, 2]. Therefore, it was imperative to seek eco-friendly, low-cost and effective technologies for completely eliminating multidrug-resistant pathogenic bacteria [3, 4]. Compared with conventional water purification methods, including chlorination, ozonation and UV irradiation, photocatalytic inactivation based on semiconductors has been widely accepted as one of the most promising alternative techniques due to its excellent photocatalytic activity, favorable reusability, nontoxic and stable inactivation properties [5–7].

Compared to traditional semiconductors, such as TiO$_2$, WO$_3$, graphitic carbon nitride (g-C$_3$N$_4$, CN), a visible-light-driven photocatalyst has triggered considerable attraction in virtue of its suitable bandgap, low cost, convenient preparation, nontoxicity, as well as excellent physicochemical stability, thus resulting in an especially suitable application for photocatalytic inactivation of pathogenic bacteria [8–10]. Despite these above advantages, CN was severely suffered from its intrinsic drawbacks of poor specific surface area, insufficient visible light response and high photoexcited charge recombination in practical application [11, 12]. Consequently, various efforts have been devoted to improve the photocatalytic performance of CN, including porous morphology control, heteroatoms introduction, noble metal deposition and heterojunctions construction, etc. [13–15] Within them, nonmetal doping (O, S, B, P, C) was one of the most effective strategies.
to enhance the photocatalytic activity of CN by regulating the electronic structure and facilitating the charge migration [16–20]. In addition, constructing p-n type heterojunction with metal oxides or metal sulfides has been considered to be another effective technique for improving photocatalytic property due to its unique charges transfer form, which not only significantly promoted the separation efficiency of charges but also prolonged the lifetime of photoexcited holes and electrons [21]. Hitherto, numerous of CN based p-n heterojunctions, such as Cu1.96S/g-C3N4, Cu2O/g-C3N4, Bi2O3/g-C3N4 and Mn3O4/g-C3N4, have been successfully fabricated and exhibited unusually efficient photocatalytic activity for bacteria inactivation or pollutants degradation [22–25].

The photocatalytic activity of semiconductors was significantly affected by the synthesis method. Compared to traditional techniques of Sol-Gel, wet-chemical and solvothermal, ultrasonic synthesis has been regarded as a facile, effective and green method. Thus, various photocatalysts fabricated by sonochemistry technique, for example Ag2CrO4-C, La5Sn2O7/g-C3N4 nanocomposites, have been confirmed to exhibit excellent photocatalytic performance [26, 27].

Recently, Ag2S, a narrow bandgap p-type semiconductor (∼1.0 eV), has been discovered as a novel visible-to-near-infrared driven photocatalyst for efficient photocatalytic degradation of pollutants and H2 production [28, 29]. Nevertheless, the photocatalytic efficiency of bare Ag2S was also greatly restricted by the severe recombination rate of photoexcited charges [30]. Therefore, it is imperative to construct a g-C3N4 based p-n heterojunction with Ag2S for increasing their photocatalytic activity.

Herein, taking the advantages of p-n heterojunction and ultrasonic synthesis, a simple two-step process was applied to construct 0D/2D Ag2S/PCN heterostructure. And the photocatalytic performance of as-prepared composites toward E. coli inactivation was evaluated. Results exhibited that the obtained 0D/2D Ag2S/PCN heterostructures possess superior photocatalytic performance in inactivation of E. coli. The enhanced visible light capture ability and accelerated photoexcited charges separation efficiency were interrelated and together affected the performance of photocatalytic inactivation.

2. Experimental section

All the reagents with analytical grade purity were purchased from Aladdin Co., Ltd (Shanghai, China) and used directly without any further treatment. The deionized water applied in all processes was supplied by Milli-Q System (≥18.2 MΩ cm−1).

2.1. PCN composites preparation

The phosphorus-doped g-C3N4 was prepared by one-pot calcination the mixture of urea and ammonium phosphate according to the previous publication with slight modifications [19]. Specifically, 20 g urea and 0.5 g ammonium phosphate were mixed thoroughly into 5 ml deionized water and then kept stirring at 80 °C to completely evaporate the excess water. Afterwards, the resultant mixture was calcined for 120 min in a covered crucible at 520 °C with a ramp rate of 5 °C·min−1 under atmosphere. After cooling down to ambient temperature naturally, the resulted powder was labeled as PCN.

Similarly, the pristine g-C3N4 were obtained by direct calcinating of urea using the same procedure and the obtained product was named as CN.

2.2. 0D/2D Ag2S/PCN heterostructures fabrication

The 0D/2D Ag2S/PCN heterostructures with different weight ratios of Ag2S were fabricated by means of an ultrasonic-assisted synthesis technique, and the typical program was as follows: 0.5 g PCN was dispersed into 50 ml of deionized water completely by ultrasonication, and then AgNO3 (13.6, 27.2, 68.0, 136.0 mg) were dissolved into above suspension. The mixture was subjected to ultrasonic treatment at 40 kHz with the power of 250 W for 30 min to ensure the complete adsorption of Ag+ onto the surface of PCN. Subsequently, the equivalent Na2S in 50 ml deionized water was quickly added and kept further ultrasonication for 30 min. Finally, the products were collected, washed with deionized water, fully dried at 80 °C, and products were denoted as Ag2S/PCN-1, Ag2S/PCN-2, Ag2S/PCN-5 and Ag2S/PCN-10 (1, 2, 5, 10 represented the mass ratio of Ag2S to PCN), respectively.

2.3. Composites characterization

The crystal structure of as-prepared samples was analyzed by x-ray diffractometry (XRD, Bruker D8 Advance, Germany). The morphology and microstructure of the composites were characterized on scanning electron microscopy (SEM, Hitachi SU8010, Japan) equipped with an energy dispersive x-ray spectrometric microanalysis (EDS) unit and transmission electron microscopy (TEM, JEM 2100 F, Japan). The surface element chemical states were investigated on an x-ray photoelectron spectroscopy (XPS, Thermo Fisher ESCALAB 250Xi, USA). The UV–vis diffuse reflectance spectra (DRS) were recorded on a spectrophotometer (Shimadzu,
UV-2450, Japan) using BaSO$_4$ as a reference. The electron paramagnetic resonance (EPR) signals were measured on a Bruker A300 spectrometer.

The photoelectrochemical properties of as-prepared composites, such as photocurrent response, electrochemical impedance spectroscopy (EIS) measurements were operated on electrochemical workstation (CHI-660E, Chen Hua, China) with a conventional three-electrode configuration. During the experiments, a 300 W xenon lamp with a UV cut-off filter ($\lambda > 420$ nm) was employed as visible light source, and 0.5 M Na$_2$SO$_4$ was selected as supporting electrolyte. The working electrode was prepared according to published literature [28].

2.4. Photocatalytic inactivation performance assessment

In this work, the multidrug-resistant E. coli isolated from the hospital wastewater was chosen as the targeted bacteria to evaluate the photocatalytic inactivation performance of as-prepared composites. A 300 W xenon lamp equipped with a 420 nm cut-off filter was employed as the irradiation source to drive the photocatalytic inactivation reaction. In a typical reaction, 20 mg as-prepared composites were completely dispersed into 99 ml sterilized deionized water through 30 min of ultrasound treatment at 25 °C. And then 1.0 ml of logarithmic growth of E. coli (about 10$^9$ CFU·ml$^{-1}$ in sterilized 0.9% saline solution) was injected into the above solution. At the planned time intervals, 0.1 ml of the serially diluted solution were uniformly spread on Luria-Bertani nutrient agar plates. After being incubated at 37 °C for 18 h, the number of colonies were counted for analysis of the cell survival. Meanwhile, for comparison, the light control experiment groups (without composites) and dark control experiment (composites alone without light) were also investigated.

The free radicals trapping experiments were carried out to reveal the inactivation mechanism by introducing different trapping agents into the inactivation system to capture the corresponding radical species, where 1-Oxyl-2, 2, 6,6-tetramethyl-4-hydroxypiperidine (TEMPOL), ammonium oxalate (AO), isopropanol (IPA) and potassium dichromate ($K_2Cr_2O_7$) with the same concentration of 2 mM were used as scavengers of $O_2^-$, $h^+$, $'OH$, and $e^-$, respectively [31, 32]. All bacterial inactivation experiments were performed in triplicate.

3. Results and discussions

3.1. Characterization of the as-prepared composites

Firstly, the structure of as-prepared composites was characterized by XRD and the results were described in figure 1. It could be seen that all the samples exhibited the typical diffraction peaks of CN deriving from the heptazine structure (JCPDS No. 87–1526) [33], indicating the frameworks of CN was largely retained after doping and ultrasonic treatments. However, compared to pristine CN, the intensity of the (002) diffraction peak became gradually smaller and broader with the increasing weight ratios of Ag$_2$S, suggesting the introduction of structural defects in Ag$_2$S/PCN framework caused by the effect of Ag$_2$S introduction and ultrasonic cavitation [34]. Obviously, the characteristic peaks of Ag$_2$S were almost undetectable in all of the Ag$_2$S/PCN composites, possibly due to the low anchoring content or a highly dispersed state [35].

The typical morphologies and fine nanostructures of Ag$_2$S/PCN-5 were depicted by SEM and TEM. As shown in figures 2(a) and (b), the Ag$_2$S/PCN-5 exhibited irregular lamellar structure with wrinkles, and numerous nanoparticles corresponding to Ag$_2$S anchored on its surface. As expected, EDS mapping images in figures 2(c)–(h) presented a uniform distribution of C, N, P, O, S and Ag elements in Ag$_2$S/PCN-5. In the EDX...
spectrum (figure 2(i)), the peaks of C, N, P, O, Ag and S were also identified clearly, illustrating the formation of heterojunctions between PCN and Ag2S. This 0D/2D structure of Ag2S/PCN-5 was further confirmed by HR-TEM images. Figures 3(a) and (b) revealed that Ag2S/PCN-5 displayed a loose two-dimensional structure consisting of small wrinkled sheets. And abundant of black dots relating to Ag2S uniformly dispersed on the surface of PCN with a diameter of 5–10 nm. Furthermore, the lattice fringes with spacing of 0.26 nm could be detected in Ag2S, which was in good agreement with the (121) interplanar spacing of monoclinic Ag2S (JCPDS No. 14–0072).

Combined the SEM and HR-TEM results, it was quite reasonable to conclude that the 0D/2D heterostructure of Ag2S/PCN has been successfully constructed.

The surface compositions and chemical states of Ag2S/PCN-5 were confirmed by XPS. Obviously, C, N, P, O, S and Ag elements existed on the surface of Ag2S/PCN-5 from the survey spectra (figure 4(a)). For the high-resolution of C1s in figure 4(b), the spectra could be well divided into three peaks located at 284.8, 286.3 and 517.8 eV.
288.3 eV, which corresponded to C–C, C–N/C=N, N=C=N bonds from the tri-s-triazine subunits, respectively [36]. Figure 4(c) depicted the high-resolution spectra of N1s, which was deconvoluted into three peaks centered at 398.7, 400.1, 401.1 eV, representing the aromatic N with sp2-hybridized (C–N=C), N combined with three adjacent C atoms and amino functional groups (–NH2) at the structural edges of PCN, correspondingly [37]. In particular, the P 2p spectra (figure 4(d)) exhibited three peaks with binding energies of 133.3, 133.9 and 134.6 eV, which could be ascribed to P–N, P=N and P=O bonds, indicating the displacement of C atoms by P atoms in the tri-s-triazine subunits [19, 31]. While for the O 1s spectra (figure 4(e)), a broad peak at 532.5 eV possibly derived from the surface adsorbed H2O or the group of PO43−. As for S 2p spectra (figure 4(f)), the two peaks at around 161.0 and 162.2 eV were ascribed to S 2p3/2 and S 2p1/2 in Ag2S, correspondingly [29]. The doublet characteristic peaks of Ag 3d3/2 (373.9 eV) and Ag 3d5/2 (369.9 eV) were detected in Ag5d spectra (figure 4(g)), which correspond to the characteristic peaks of Ag⁺ [38].

The existence of C defects induced by the doped P atoms was firmly validated by the ESR spectra. As depicted in figure 4(f), all samples possessed a typical EPR signal at a g value of 2.004, which was attributed to the unpaired electrons in the aromatic C=N heterocycles [39]. Moreover, compared with CN, PCN and Ag2S/PCN revealed much higher EPR signal intensities, indicating more C defects in the as-prepared composites, which was mainly ascribed to the substitution of P to C atoms and the anchoring of Ag2S nanoparticles on the surface of PCN. These unpaired electrons could facilitate the production of photoexcited charges, resulting in the highly efficient photocatalytic properties [40].

The optical properties and electronic structures of the as-prepared PCN, Ag2S and Ag2S/PCN composites were measured by UV–vis DRS spectra. From figure 5(a), PCN possessed obvious visible light absorption with an absorption edge at about 450 nm. In comparison with PCN, after being anchored of Ag2S, the Ag2S/PCN heterostructures exhibited observably improved absorption in visible-light region as the increasing Ag2S amount. The improved visible light harvesting capability of Ag2S/PCN heterostructures could enhance the visible light utilization, which favored the remarkably increased photocatalytic inactivation performance. The corresponding band gaps were estimated according to the following equation:

\[ a h v = A \left( h v - E_g \right)^{n/2} \]

where the value of n for PCN was 2 and Ag2S was 4, respectively [36, 41].

As shown in figure 5(b), the \( E_g \) values of PCN and Ag2S were calculated to be 2.64 and 0.98 eV. Subsequently, the valence band (\( V_B \)) and conduction band (\( C_B \)) potentials of PCN and Ag2S were calculated based on the following formula:

\[ E_{VB} = X - E_c + 0.5E_g \]
\[ E_{CB} = E_{VB} - E_g \]

Figure 3. TEM (a), (b) and HR-TEM images (c) of Ag2S/PCN-5; Size distribution of Ag nanoparticles on PCN surface.
Where $X$ is the electronegativity of the semiconductor (PCN $\sim$ 4.73 eV, Ag$_2$S $\sim$ 4.97 eV) [28, 31], $E_e$ is the energy of free electrons on the hydrogen scale ($\sim$ 4.50 eV). Therefore, the $E_{VB}$ and $E_{CB}$ of PCN were determined to be 1.55 and $-1.09$ eV, while those of Ag$_2$S were 0.96 and $-0.02$ eV, respectively.

Figure 4. XPS survey spectra (a), the corresponding high-resolution spectra of C 1 s (b), N 1 s (c), P 2p (d), O 1 s (e), S 2p (f) and Ag 3d (g) for Ag$_2$S/PCN-5; and ESR spectra of CN, PCN and Ag$_2$S/PCN-5 (h).
To further explore the band structure, valence band (VB) - XPS was carried out to assess the VB level relative to Fermi level ($E_F$). As shown in figure 5(c), the energy difference between the $E_F$ and the valence band maximum (VBM) of PCN was determined to be 2.08 eV, while that of Ag$_2$S was 0.26 eV. Correspondingly, the band structural parameters of PCN and Ag$_2$S were conducted. As illustrated in figure 5(d), the $E_F$ was near the CB bottom for PCN and near the VB top for Ag$_2$S, indicating that PCN was a n-type semiconductor, while Ag$_2$S was a p-type semiconductor, which were in accordance with the previous studies [42, 43]. On this basis, the integration of PCN and Ag$_2$S was expected to construct a p-n heterostructure to accelerate the charge separation and migration at the interface, leading to an efficient photocatalytic inactivation performance.

3.2. Photocatalytic inactivation performance of as-prepared composites

The visible-light-driven photocatalytic performance of as-prepared composites was evaluated by inactivating of multidrug-resistant E. coli. As shown in figure 7(a), the selected E. coli demonstrated significant resistant to ampicillin and clindamycin, while sensitive to gentamicin, which was a serious threat to human health. Incubation with composites in dark or exposure to visible light radiation for 60 min, the cell number was almost the same as the initial bacterial population, meaning the minimal toxicity of these composites and visible light (figure 6(a)). Under visible light irradiation, different composites displayed certain inactivation activity (figure 6(b)). For pristine CN, PCN and Ag$_2$S, there were only 1.4, 2.3 and 2.6-log reduction of E. coli was achieved after irradiation for 60 min, illustrating a slight photocatalytic inactivation performance of pristine CN, PCN and Ag$_2$S. Strikingly, for Ag$_2$S/PCN heterostructures, the photocatalytic inactivation efficiencies were dramatically enhanced with the decreased living cells number of 3.4, 5.1 7.0 and 6.2-log corresponding to Ag$_2$S/PCN-1, Ag$_2$S/PCN-2, Ag$_2$S/PCN-5 and Ag$_2$S/PCN-10, respectively. In particular, Ag$_2$S/PCN-5 exhibited the highest inactivation performance with no colonies left on the plate within 60 min of visible-light irradiation (figure 7(f)). In addition, the reduction of bactericidal performance of Ag$_2$S/PCN-10 might be because that the excessive load of Ag$_2$S could act as the recombination center of photogenerated charges or might occupy the active sites on the surface of PCN to restrict the photocatalytic performance [44, 45].

The reusability and stability of photocatalysts were very crucial for the practical application in water purification. As plotted in figure 8, in three recycles, the photocatalytic inactivation activity of Ag$_2$S/PCN-5 was still maintained at high levels with 7.0, 6.6 and 6.2-log of reduced cell viability. This result indicated that Ag$_2$S/PCN-5 exhibited excellent stability in disinfection process.
3.3. Photocatalytic mechanism of Ag$_2$S/PCN-5 heterostructure

It was generally accepted that the reactive oxidizing species, such as $\cdot$O$_2^-$, $\cdot$OH, $h^+$ and $e^-$ were responsible for the photocatalytic inactivation process [46]. Thus, a serial of radicals trapping experiments were carried out to reveal in the photocatalytic inactivation mechanism of Ag$_2$S/PCN-5, in which, TEMPOL, AO, IPA and K$_2$Cr$_2$O$_7$ were employed as scavengers of $\cdot$O$_2^-$, $h^+$, $\cdot$OH, and $e^-$, respectively. As described in figure 9(a), introduction IPA and K$_2$Cr$_2$O$_7$ as the scavengers of $\cdot$OH, and $e^-$, there was only 1.52 and 2.03-log of viable cells were detected, suggesting that $\cdot$OH, and $e^-$ were negligible in photocatalytic inactivation process. While addition of TEMPOL, the inactivation performance was significantly suppressed, indicating the $\cdot$O$_2^-$ performed an indispensable role in this inactivation system. Furthermore, most remarkably, the photocatalytic inactivation activity of Ag$_2$S/PCN-5 was dramatically decreased in the presence of AO, demonstrating that the $h^+$ was the crucial reactive specie in the photocatalytic inactivation process.

To demonstrated the generation of reactive radical species of $\cdot$O$_2^-$ and $\cdot$OH over Ag$_2$S/PCN-5 system. Nitro blue tetrazolium (NBT) and terephthalic acid (TA) were employed as acceptors for $\cdot$O$_2^-$ and $\cdot$OH [47, 48]. As shown in figure 9(b), the gradually decreased absorbance of NBT was observed with extended irradiation time.

![Figure 6.](image-url)  
Inactivation efficiencies of as-prepared composites toward E. coli in dark (a) and under visible-light irradiation (b).
suggesting abundant $\cdot$O$_2^-$ produced in Ag$_2$S/PCN-5 system. As for $\cdot$OH in figure 9(c), there was a very weak fluorescence intensity was detected, indicating slight $\cdot$OH was generation, which were consistent with the results of radicals trapping experiments.

For better revealing the enhanced inactivation mechanism of Ag$_2$S/PCN-5, the photochemical properties, like PL, EIS and photocurrent response measurements were carried out. Obviously, it could be seen from figure 10(a) that the PL intensity of Ag$_2$S/PCN-5 was evidently much lower than that of CN and PCN, which
expounded that the recombination rate of the photogenerated charges was restrained by this 0D/2D heterostructure [49]. The EIS method is another technology to prove the separation efficiency of the photogenerated charge. The smaller arc radius means a higher separation efficiency of photogenerated carriers [50]. Figure 10(b) presented the EIS Nyquist plots of the tested samples, and Ag2S/PCN-5 possessed minimum arc radius compared to CN and PCN, which reflected the huge reduced transfer resistance of free charges and elevated charge transfer ability [51]. From the photocurrent response spectra in figure 10(c), Ag2S/PCN-5 exhibited the optimal photocurrent intensity and was increased about 2.5 and 2.0 times more than CN and PCN, which was also in accordance with the excellent photocatalytic inactivation performance.

According to the above results, the possible p-n heterojunction-based reaction diagram of Ag2S/PCN-5 on photocatalytic inactivation was predicted in figure 11. Before contacting, the E_F of n-type PCN was close to the CB, while that of p-type Ag2S was close to the VB (Left of figure 11). When Ag2S nanoparticles decorating on the surface of PCN, the p-n heterostructure would be constructed and the charge would be redistributed between PCN and Ag2S, resulting in the energy levels of Ag2S shifted upward, whereas those of PCN shifted downward until the E_F of both Ag2S and PCN eventually reached an equilibrium, which resulted in the formation of an internal electric field in their contacted interface. Namely, the electrons would diffuse from PCN (higher E_F) to Ag2S (lower E_F), while the holes would transfer from Ag2S to PCN, rendering Ag2S negatively charged and making PCN positively charged at the interfacial region (Right of figure 11).

Once the heterostructure was illuminated by visible light, the photoexcited electrons and holes could be generated simultaneously on the Ag2S and PCN surfaces. Owing to the favorable band structure, the holes generated in the VB of PCN would migrate and accumulate on the VB of Ag2S. Meanwhile, the electrons in the CB of Ag2S were transferred and accumulated on the CB of PCN. As a result, the recombination of photoexcited carriers was effectively suppressed, providing longer surviving electrons and holes. The accumulated electrons on the CB of PCN could capture dissolved O2 to form huge ‘O2’ because the CB potential of PCN (−1.09 eV versus NHE) was negative to E°(O2/O2−) (−0.33 eV versus NHE) [52], which could also be further partially converted to ‘OH through complex processes. Unfortunately, the accumulated holes retained at the VB of Ag2S

Figure 10. PL (a), EIS (b) and time-dependent photocurrent response (c) of CN, PCN and Ag2S/PCN-5.
could not produce 'OH via oxidizing H₂O/OH⁻ because of the more negative potential relative to the standard redox potential of 'OH/OH⁻ (E° = 1.99 V versus NHE) [53]. Nevertheless, the accumulated holes could directly inactivate the bacteria because of their strong oxidizing capacity. Consequently, the p-n type heterojunction of Ag₂S/PCN effectively promoted the separation and utilization of photoexcited carriers, leading to the enhancement of photocatalytic inactivation activity.

4. Conclusions

In brief, a novel 0D/2D Ag₂S/PCN p-n heterojunction was successfully fabricated via a facile calcination combined ultrasonic irradiation. The resultant composite achieved excellent photocatalytic inactivation activity toward multidrug-resistant E. coli. Under visible light, the optimum composite of Ag₂S/PCN-5 could absolutely inactivate 7.0-log E. coli cells in 60 min. The enhanced photocatalytic inactivation activity was attributed to the p-n heterostructure of Ag₂S/PCN, which dramatically accelerated the separation of photo-generated charges, meanwhile imparted high redox ability to the heterojunction. Such a facile strategy may provide a promising prospect for designing and constructing other high efficiency g-C₃N₄ or Ag₂S based photocatalysts to deal with resistant pathogenic bacteria pollution in water.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest

The authors declare no competing financial interest.

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