Photocatalytic Application in Energy and Environmental Sustainability

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The energy and environmental crises have been an ongoing challenge, which is related to the vital interests of people around the globe. How to solve this problem through sustainable development strategies is considered deeply by scientific researchers. Photocatalysis provides a powerful technique for fully utilizing solar in the field of energy conversion.

g-C3N4 preparation modification hydrogen evolution CO2 conversion

1. H_2 Production

Hydrogen is gathering strong momentum as a pivotal energy transition pillar driven by the global shift toward decarbonization. Nevertheless, 85% of H_2 is produced from fossil fuel combustion, which generates roughly 500 metric tons of carbon dioxide every year and proffers a challenge and obstacle toward the sustainable living of future generations [1]. Solar-driven photocatalytic H_2 generation as a promising technology has received extensive attention in addressing the global energy crisis [2][3]. Photocatalytic water splitting for the energy transformation from solar to eco-friendly fuels has been studied for decades with various semiconductor photocatalysts. As a type of semiconductor photocatalyst, g-C_3N_4 is simple and inexpensive to fabricate, and has an adequate bandgap (≈2.7 eV) for activation upon sunlight irradiation. Wang's group first utilized g-C_3N_4 in photocatalytic H_2 evolution [4][5]. Nonetheless, pristine g-C_3N_4 is far from satisfactory energy conversion because of its low light energy utilization, low density active sites, and ineffective isolation of the photogenerated excitons. Thus, researchers have proposed numerous strategies to boost the photocatalytic activity of g-C_3N_4-based materials for H_2 production. For example, the g-C_3N_4/carbon-dot-based nanocomposites, which possess enormous visible light absorption and applicable energy structures, have been prepared and serve as efficacious photocatalysts in photocatalytic water splitting for H_2 generation under light illumination [3][6][7][8]. Gao et al. reported hexagonal tubular g-C_3N_4/CD-based nanocomposites which exhibited nine times higher than bulk g-C_3N_4 in H_2 production rate [3] and related results indicated that CDs performed as both photosensitizer and electron acceptor. CDs could absorb long wavelength light to extend the visible-light response region and suppress the recombination of electron-hole pairs. Hussien et al. [9] combined four different strategies (non-metal doping, porosity generation, functionalization with amino groups, and thermal oxidation etching) in a one-pot thermal reaction and successfully prepared amino-functionalized ultrathin nanoporous B-doped g-C_3N_4 by using NH_4Cl as a gas bubble template, together with a thermal exfoliation process to produce ultrathin sheets. According to the process, the surface area, adsorption

capacity, and charge migration of the as-prepared photocatalyst have been improved, and a 3800 μmol g^{-1} h^{-1} H_2 generation rate and 10.6% prominent quantum yield were recorded. Li et al. [10] decorated carbon self-doping g-C_3N_4 nanosheets with gold-platinum (AuPt) nanocrystals through a photo-deposition route and compared the photocatalytic H_2 evolution performance of Pt/CCN, Au/CCN, Au/Pt/CCN, and Pt/Au/CCN, in which AuPt/CCN stood out and gave the highest H_2 generation rate (1135 μmol h^{-1}). The excellent performance can be ascribed to the non-plasmon-related synergistic effect of Au and Pt atoms in AuPt nanocrystals. Sun et al. [11] assessed the arrangements of metal- and non-metal-modified g-C_3N_4 composites in hydrogen evolution and found that the contribution of dye conjugation in non-metallic g-C_3N_4 composites favored their performance. However, the co-catalyst doping strategy was recommended for metallic g-C_3N_4 composites. In addition, the hybrid of MOF materials and g-C_3N_4 is also a good approach to develop novel photocatalysts. For example, Devarayapalli et al. [12] reported a g-C_3N_4/ZIF-67 nanocomposite and obtained a 2084 μmol g^{-1} H_2 production, which is 3.84-fold greater than that of bare g-C_3N_4.

2. CO_2 Photoreduction over g-C_3N_4

Rising atmospheric levels of CO_2 and the consumption of fossil fuels raise a concern about the continued reliance on the utilization of fossil fuels for both energy and chemical production [13]. Photocatalytic reduction of CO_2 is a promising strategy to meet increasing energy needs and reduce the greenhouse effect [14]. Through photocatalytic reduction, CO_2 can be converted to light oxygenates and hydrocarbons. Photocatalytic CO_2 reduction is a multielectron transfer process. Fu et al. [15] have listed the possible reaction and corresponding redox potentials and stated that CO_2 was complicated to reduce at room temperature due to its stable chemical structure. For the complex reaction, five factors, comprising the matching of band energy, separation of charge carrier, kinetic of e- and hole transfer to CO_2 and reductant, the basicity of photocatalyst, and the strength and coverage of CO_2 adsorption, are considered to be crucial [16]. As a hot member of photocatalysts, g-C_3N_4 has been applied to CO_2 photo-reduction in recent years because the CB of g-C_3N_4 is sufficient to reduce CO_2 to various hydrocarbons, such as CH_3OH, CH_4, HCHO, and HCOOH and so on. [17].

However, metal-free g-C_3N_4 is limited for CO_2 reduction activity due to its poor ability to activate the C-O bond of CO_2. To improve the photocatalytic movement of CO_2 conversion, different metal units have been composited with g-C_3N_4 for broadening the absorption response range, and accelerating the charge separation and transfer, such as Pt/g-C_3N_4 [18], Co^{2+}/g-C_3N_4 [19][20], Au/g-C_3N_4 [21] and so on. Metal nanoparticles acting as cocatalysts could effectively improve the photocatalytic activity and selectivity of CO_2 reduction. In addition, other methods, including doping, loading cocatalysts and nanocarbons, constructing *Z*-scheme, and heterojunction, have also been employed [22][23][24][25][26][27][28][29][30]. For example, Fu et al. [31] prepared hierarchical porous *O*-doped g-C_3N_4 nanotubes (OCN-Tube) through continuing thermal oxidation exfoliation and curling condensation of bulk g-C_3N_4. Due to the higher specific surface area, better light harvesting, higher CO_2 uptake capacity, and superior separation efficiency of photogenerated charge carriers, the OCN-Tube exhibits excellent photocatalytic CO_2 reduction performance into CH_3OH. The CH_3OH evolution rate was as high as 0.88 μmol g^{-1} h^{-1}, five times higher than the bulk (0.17 μmol g^{-1} h^{-1}). Huo et al. [32] fabricated amine-modified step-scheme (*S*-scheme) porous g-

C_3N_4/CdSe-diethylenetriamine (A-PCN/CdSe-DETA) by a one-step microwave hydrothermal method. The modification by amine and formation of *S*-scheme heterojunction contributed to the remarkable photocatalytic performance of A-PCN/CdSe-DETA composite in CO_2 reduction and a CO production rate of 25.87 μmol/(h g) was achieved under visible-light irradiation. Wang et al. [14] reviewed different modification methods of g-C_3N_4-based photocatalysts for CO_2 reduction. They discussed each method (including morphology adjustment, co-catalysts, heterostructures, and doping) and compared the theoretical calculations and experimental results. By morphology adjustment, g-C_3N_4 with various shapes can be fabricated, such as rods, tubes, nanosheets, hollow spheres, and honeycomb-like structures. Due to the advantage of cocatalysts (e.g., Au, Ag, Pt, Pd, MXene, AuCu alloy, Pd-Ag), g-C_3N_4 with co-catalysts can be widely applied to activate CO_2 on the surface. Heterojunction with different types is also an effective method to improve the properties of g-C_3N_4-based materials. In addition, elemental doping is considered a common method to enhance photocatalytic quantum efficiency by changing the energy band, surface electronic property, and electrical conductivity.

3. Degradation of Organic Pollutants

Along with rapid population growth and significant industrialization development, large numbers of toxic, hazardous, and endless contaminants invade the environment, threatening to human life, especially a variety of pollutants present in water that are difficult to eliminate or degrade naturally. Photocatalytic degradation of contaminants is a green and efficient technology for coping with sewage [6][33]. Different kinds of g-C_3N_4-based materials (**Table 1**) have been exploited to increase the photodecomposition efficiency of pollutants, such as the constructed heterojunction, loading O_2-reduction co-catalysts, g-C_3N_4/CDs-based nanocomposites, and so on [23][34][35][36]. Generally, under the irradiation of visible light, the photogenerated electrons (e^-) on the g-C_3N_4 catalyst will be excited from VB to CB, leaving holes (h^+) in the VB. The holes can oxidize pollutants directly or react with H_2O/OH^- to form hydroxyl radicals [37]. When the REDOX potential of g-C_3N_4 composites is more negative than O_2/O_2^-, the photogenerated electrons in the material can react with O_2 to produce O_2^- with strong oxidation capacity [38]. In addition, the resulting O_2^- could be protonated to produce OH [39]. Finally, the RhB dye is degraded to CO_2 and H_2O under the action of these free radicals. Chen et al. [40] fabricated a $BiFeO_3$/g-C_3N_4 heterostructure through mixing-calcining and compared its performance with $BiFeO_3$. Around 30% higher photocatalytic efficiency toward RhB dye was observed for the $BiFeO_3$/10% g-C_3N_4 heterostructure, which was assigned to the contribution of a higher concentration of O_2^-. Zhang et al. [41] studied the selective reduction of molecular oxygen on g-C_3N_4 and probed its effect on the photocatalytic phenol degradation process. Compared with bulk g-C_3N_4, the exfoliated nanosheet yielded a three times improvement in photocatalytic phenol degradation. It has been demonstrated that bulk g-C_3N_4 prefers to reduce O_2 to O_2^-via one-electron reduction. At the same time, the photoexcited g-C_3N_4 nanosheet facilitates the two-electron reduction of O_2 to yield H_2O_2 because of the formation of 1,4-endoperoxide species. The two-electron reduction of O_2 on the nanosheet surface boosts hole generation and thus accelerates phenol oxidation degradation [41][42]. Thus, to improve the photocatalytic performance of g-C_3N_4, more effort should be devoted to strengthening the solid O_2-reduction reactions. For example, Liu et al. [43] reported a heterojunction material of K-doped g-C_3N4 nanosheet -CdS and degraded tetracycline with 94% degradation under visible light in 30 min. In addition, due to the electronegativities, ionic radius differences, and impurity states, element doping is

also an effective method to manipulate the electronic structure and physicochemical performance of g-C_3N_4-based materials. Gao et al. [44] synthesized Fe-doped g-C_3N_4 nanosheets and obtained 1.4- and 1.7-fold higher degradation rates of MB than that of pure g-C_3N_4 nanosheets and bulk g-C_3N_4, which indicated that the exploitation of efficient g-C_3N_4-based photocatalysts with high stabilization and degradation under visible light irradiation would significantly contribute to sewage disposal. Zhang et al. [45] synthesized a novel hybrid of Zr-based metal-organic framework with g-C_3N_4 (UiO-66/g-C_3N_4) nanosheets and applied a photodegradation of methylene blue, by which a 100% photodegradation was achieved within 4 h under visible light. Here, it has been provided with a new insight into the design of g-C_3N_4-based photocatalysts to deal with organic dyes in the environment.

Table 1. Photocatalytic degradation of pollutants over g-C_3N_4-based materials reported within the last three years.

Entry	Photocatalyst	Pollutant Concentration	Light Source	Degradation Efficiency/%	Ref.
1	5% g-C_3N_4-TiO_2	Acetaminophen: 0.033 mM	300 W Xe (>400 nm)	99.3 in 30 min	[46]
2	3ZIF/1.5Au-PCN	Bisphenol A	350 W Xe (>420 nm)	>85%	[47]
3	Cu(tmpa)/20%CN	Congo red: 100 mg·L^{-1}	150 W Xe	98.2% in 3 min	[48]
4	BiO-Ag(0)/C_3N_4@ ZIF-67	Congo red: 12 mg·L^{-1}	Natural sunlight	90% in 150 min	[49]
5	C_3N_4/RGO/$Bi_2Fe_4O_9$	Congo red: 10 mg·L^{-1}	LED 30 W	87.65% in 60 min	[50]
6	g-C_3N_4/Co-MOF	Crystal violet: 4 ppm	MaX 303 solar simulator (50 mW/cm)	95% in 80 min	[12]
7	Honeycomb-like g-C_3N_4/CeO_2-x	Cr (VI): 20 mg·L^{-1}	300 W Xe (>420 nm)	98% in 150 min	[51]
8	Sm_6WO_{12}/g-C_3N_4	Levofloxacin: 10 mg·L^{-1}	150 Mw cm^{-2} tungsten lamp	98% in 70 min	[52]
9	O-g/C_3N_4	Lincomycin: 100 mg·L^{-1}	PCX50C system (>420 nm)	99% within 3 h	[53]
10	ZnO-modified g-C_3N_4	Methylene blue: 10 ppm	200 W tungsten lamp (>420 nm)	97% in 80 min	[54]
11	Wood-like g-C_3N_4@WDC	Methylene blue: 20 mg·L^{-1}	300 W Xe (>400 nm)	98% in 60 min	[55]

Entry	Photocatalyst	Pollutant Concentration	Light Source	Degradation Efficiency/%	Ref.
12	BiO-Ag(0)/C_3N_4@ ZIF-67	Methylene blue: 12 mg·L^{-1}	Natural sunlight	96.5% in 120 min	[49]
13	Cerium-based GO/g-C_3N_4/Fe_2O_3	Methylene blue: 10 mg·L^{-1}	Light bulb	70.61% in 45 min	[56]
14	Ytterbium oxide-based GO/g-C_3N_4/Fe_2O_3	Methylene blue: 10 mg·L^{-1}	Light bulb	83.5% in 45 min	[56]
15	Cu(tmpa)/20%CN	Methylene blue: 10 mg·L^{-1}	150W Xe	92.0% within 20 min	[48]
16	C_3N_{4x}/AgO_y@$Co_{1-x}Bi_{1-y}O_7$	Methylene blue: 25 mL 10 mM	100 W tungsten bulb	96.4% in 120 min	[57]
17	Ternary composites of Zr-MOF combined with g-C3N4 and Ag_3PO_4	Methylene blue: 10 mg·L^{-1}	85-watt tungsten lamp outdoor/solar light in an open air	95% within 240 93% within 105 min	[58]
18	PSCN/Ag@AgI/WO_3	Malachite green: 1 × 10^{-4} mol dm^{-3}	35 W LED	90% in 60 min	[59]
19	Cu(tmpa)/20%CN	Malachite green: 30 mg·L^{-1}	150W Xe	92.9% in 35 min	[48]
20	20% g-C_3N_4/$Bi_4O_5I_2$	Methyl orange: 20 mg·L^{-1}	350 W Xe	0.164 min^{-1}	[60]
21	Cu(tmpa)/20%CN	Methyl violet: 10 mg·L^{-1}	150W Xe	92.0% in 60 min	[48]
22	$MnCo_2O_4$/g-C_3N_4	Nitrobenzene: 40 mg L^{-1}	CMCN2/PMS system	96.7% in 240 min	[61]
23	C_3N_{4x}/AgO_y@$Co_{1-x}Bi_{1-y}O_7$	Oxytetracycline: 25 mL 25 mM	100 W tungsten bulb	93% in 160 min	[57]
24	g-C_3N_4/WO_3/WS_2	Rhodamine B: 25 mg L^{-1}	300 W Xe (>420 nm)	96.2% in 20 min	[62]
25	Flower-like $Bi_{12}TiO_{20}$/g-C_3N_4	Rhodamine B: 20 mg·L^{-1}	150 mW·cm^{-2} Xe (>420 nm)	100% in 30 min	[63]
26	CdS/CQDs/g-C_3N_4	Rhodamine B: 10 mg·L^{-1}	300 W Xe (>420 nm)	100% in 20 min	[64]

Entry	Photocatalyst	Pollutant Concentration	Light Source	Degradation Efficiency/%	Ref.
27	Ytterbium oxide-based GO/g-C_3N_4/Fe_2O_3	Rhodamine B: 10 mg·L^{-1}	Light bulb	67.11% in 45 min	[56]
28	Cerium-based GO/g-C_3N_4/Fe_2O_3	Rhodamine B: 10 mg·L^{-1}	Light bulb	63.08% in 45 min	[56]
29	Fish-scale g-C_3N_4/$ZnIn_2S_4$	Tetracycline: 10 mg·L^{-1}	300 W Xe (>420 nm)	74% in 30 min	[65]
31	Flower-like Co_3O_4/g-C_3N_4	Tetracycline: 15 mg·L^{-1}	350 W Xe (>420 nm)	85.32% in 120 min	[66]
31	10 wt% $CuAl_2O_4$/g-C_3N_4	Tetracycline hydrochloride: 100 mg·L^{-1}	300 W Xe (>400 nm)	89.6% in 60 min	[67]
32	CO-C_3N_4	Tetracycline hydrochloride: 10 mg·L^{-1}	300 W Xe (>420 nm)	97.77% (PMS) in 40 min	[68]
33	ZIF-67/g-C_3N_4	Venlafaxine: 10 mg·L^{-1}	-	27.75% within 120 min	[69]
34	ZIF-67/MIL-100(Fe)/g-C_3N_4	Venlafaxine: 10 mg·L^{-1}	-	100% within 120 min	[69]
35	ZIF-67/MOF-74(Ni)/g-C_3N_4	Venlafaxine: 10 mg·L^{-1}	-	91.8% within 120 min	[69]

organic transformation. Adv. Opt. Mater. 2022, 10, 2102641.

3. Gao, Y.; Hou, F.; Hu, S.; Wu, B.; Wang, Y.; Zhang, H.; Jiang, B.; Fu, H. Graphene quantum-dot-modified hexagonal tubular carbon nitride for visible-light photocatalytic hydrogen evolution. ChemCatChem 2018, 10, 1330–1335.
4. Wang, X.; Chen, X.; Thomas, A.; Fu, X.; Antonietti, M. Metal-containing carbon nitride compounds: A new functional organic–metal hybrid material. Adv. Mater. 2009, 21, 1609–1612.
5. Ling, G.Z.S.; Ng, S.F.; Ong, W.J. Tailor-engineered 2D cocatalysts: Harnessing electron–hole redox center of 2D g-C3N4 photocatalysts toward solar-to-chemical conversion and environmental purification. Adv. Funct. Mater. 2022, 32, 2111875.
6. Asadzadeh-Khaneghah, S.; Habibi-Yangjeh, A. g-C3N4/carbon dot-based nanocomposites serve as efficacious photocatalysts for environmental purification and energy generation: A review. J. Clean. Prod. 2020, 276, 124319.
7. Shi, W.; Wang, J.; Yang, S.; Lin, X.; Guo, F.; Shi, J. Fabrication of a ternary carbon dots/CoO/g-C3N4 nanocomposite photocatalyst with enhanced visible-light-driven photocatalytic hydrogen production. J. Chem. Technol. Biotechnol. 2020, 95, 2129–2138.

8. Zhang, S.; Gao, M.; Zhai, Y.; Wen, J.; Yu, J.; He, T.; Kang, Z.; Lu, S. Which kind of nitrogen chemical states doped carbon dots loaded by g-C3N4 is the best for photocatalytic hydrogen production. J. Colloid Interface Sci. 2022, 622, 662–674.
9. Hussien, M.K.; Sabbah, A.; Qorbani, M.; Elsayed, M.H.; Raghunath, P.; Lin, T.-Y.; Quadir, S.; Wang, H.-Y.; Wu, H.-L.; Tzou, D.-L.M. Metal-free four-in-one modification of g-C3N4 for superior photocatalytic CO2 reduction and H2 evolution. Chem. Eng. J. 2022, 430, 132853.
10. Li, L.; Wang, X.; Gu, H.; Zhang, H.; Zhang, J.; Zhang, Q.; Dai, W.-L. Which Is more efficient in promoting the photocatalytic H2 evolution performance of g-C3N4: Monometallic nanocrystal, heterostructural nanocrystal, or bimetallic nanocrystal? Inorg. Chem. 2022, 61, 4760–4768.
11. Sun, Y.; Kumar, V.; Kim, K.-H. The assessment of graphitic carbon nitride (g-C3N4) materials for hydrogen evolution reaction: Effect of metallic and non-metallic modifications. Sep. Purif. Technol. 2022, 305, 122413.
12. Devarayapalli, K.; Vattikuti, S.P.; Sreekanth, T.; Yoo, K.S.; Nagajyothi, P.; Shim, J. Hydrogen production and photocatalytic activity of g-C3N4/Co-MOF (ZIF-67) nanocomposite under visible light irradiation. Appl. Organomet. Chem. 2020, 34, e5376.
13. Kamat, P.V. Meeting the clean energy demand: Nanostructure architectures for solar energy conversion. J. Phys. Chem. C 2007, 111, 2834–2860.
14. Wang, Q.; Fang, Z.; Zhang, W.; Zhang, D. High-efficiency g-C3N4 based photocatalysts for CO2 reduction: Modification methods. Adv. Fiber Mater. 2022, 4, 342–360.
15. Fu, J.; Yu, J.; Jiang, C.; Cheng, B. g-C3N4-based heterostructured photocatalysts. Adv. Energy Mater. 2018, 8, 1701503.
16. Kumar, S.; Karthikeyan, S.; Lee, A.F. g-C3N4-based nanomaterials for visible light-driven photocatalysis. Catalysts 2018, 8, 74.
17. Li, Y.; Kong, T.; Shen, S. Artificial photosynthesis with polymeric carbon nitride: When meeting metal nanoparticles, single atoms, and molecular complexes. Small 2019, 15, 1900772.
18. Zhang, L.; Long, R.; Zhang, Y.; Duan, D.; Xiong, Y.; Zhang, Y.; Bi, Y. Direct observation of dynamic bond evolution in single-atom Pt/C3N4 catalysts. Angew. Chem. 2020, 132, 6283–6288.
19. Liu, W.; Cao, L.; Cheng, W.; Cao, Y.; Liu, X.; Zhang, W.; Mou, X.; Jin, L.; Zheng, X.; Che, W. Single-site active cobalt-based photocatalyst with a Long carrier lifetime for spontaneous overall water splitting. Angew. Chem. 2017, 129, 9440–9445.
20. Pan, Z.; Zheng, Y.; Guo, F.; Niu, P.; Wang, X. Decorating CoP and Pt nanoparticles on graphitic carbon nitride nanosheets to promote overall water splitting by conjugated polymers. ChemSusChem 2017, 10, 87–90.

21. Reddy, K.R.; Reddy, C.V.; Nadagouda, M.N.; Shetti, N.P.; Jaesool, S.; Aminabhavi, T.M. Polymeric graphitic carbon nitride (g-C3N4)-based semiconducting nanostructured materials: Synthesis methods, properties and photocatalytic applications. J. Environ. Manag. 2019, 238, 25–40.
22. Ye, S.; Wang, R.; Wu, M.; Yuan, Y. A review on g-C3N4 for photocatalytic water splitting and CO2 reduction. Appl. Surf. Sci. 2015, 358, 15–27.
23. Wen, J.; Xie, J.; Chen, X.; Li, X. A review on g-C3N4-based photocatalysts. Appl. Surf. Sci. 2017, 391, 72–123.
24. Wang, K.; Li, Q.; Liu, B.; Cheng, B.; Ho, W.; Yu, J. Sulfur-doped g-C3N4 with enhanced photocatalytic CO2-reduction performance. Appl. Catal. B Environ. 2015, 176, 44–52.
25. Sun, Z.; Wang, H.; Wu, Z.; Wang, L. g-C3N4 based composite photocatalysts for photocatalytic CO2 reduction. Catal. Today 2018, 300, 160–172.
26. Ghosh, U.; Majumdar, A.; Pal, A. Photocatalytic CO2 reduction over g-C3N4 based heterostructures: Recent progress and prospects. J. Environ. Chem. Eng. 2021, 9, 104631.
27. Li, X.; Xiong, J.; Gao, X.; Huang, J.; Feng, Z.; Chen, Z.; Zhu, Y. Recent advances in 3D g-C3N4 composite photocatalysts for photocatalytic water splitting, degradation of pollutants and CO2 reduction. J. Alloys Compd. 2019, 802, 196–209.
28. Zhang, X. Layered g-C3N4/TiO2 nanocomposites for efficient photocatalytic water splitting and CO2 reduction: A review. Mater. Today Energy 2022, 23, 100904.
29. Chen, P.; Dong, X.a.; Huang, M.; Li, K.; Xiao, L.; Sheng, J.; Chen, S.; Zhou, Y.; Dong, F. Rapid self-decomposition of g-C3N4 during gas–solid photocatalytic CO2 reduction and its effects on performance assessment. ACS Catal. 2022, 12, 4560–4570.
30. Li, H.; Wang, D.; Miao, C.; Wang, Y.; Wang, Y.; Liu, C.; Che, G. g-C3N4/BiOI S-scheme heterojunction: A 2D/2D model platform for visible-light-driven photocatalytic CO2 reduction and pollutant degradation. J. Environ. Chem. Eng. 2022, 10, 108201.
31. Fu, J.; Zhu, B.; Jiang, C.; Cheng, B.; You, W.; Yu, J. Hierarchical porous O-doped g-C3N4 with enhanced photocatalytic CO2 reduction activity. Small 2017, 13, 1603938.
32. Huo, Y.; Zhang, J.; Dai, K.; Liang, C. Amine-modified S-scheme porous g-C3N4/CdSe–diethylenetriamine composite with enhanced photocatalytic CO2 reduction activity. ACS Appl. Energy Mater. 2021, 4, 956–968.
33. Nemiwal, M.; Zhang, T.C.; Kumar, D. Recent progress in g-C3N4, TiO2 and ZnO based photocatalysts for dye degradation: Strategies to improve photocatalytic activity. Sci. Total Environ. 2021, 767, 144896.
34. Duan, Y.; Deng, L.; Shi, Z.; Liu, X.; Zeng, H.; Zhang, H.; Crittenden, J. Efficient sulfadiazine degradation via in-situ epitaxial grow of graphitic carbon nitride (g-C3N4) on carbon dots

heterostructures under visible light irradiation: Synthesis, mechanisms and toxicity evaluation. J. Colloid Interface Sci. 2020, 561, 696–707.

35. Zhao, Y.; Shi, H.; Yang, D.; Fan, J.; Hu, X.; Liu, E. Fabrication of a Sb2MoO6/g-C3N4 photocatalyst for enhanced RhB degradation and H2 generation. J. Phys. Chem. C 2020, 124, 13771–13778.
36. Hayat, A.; Sohail, M.; Ali Shah Syed, J.; Al-Sehemi, A.G.; Mohammed, M.H.; Al-Ghamdi, A.A.; Taha, T.; Salem AlSalem, H.; Alenad, A.M.; Amin, M.A. Recent advancement of the current aspects of g-C3N4 for its photocatalytic applications in sustainable energy system. Chem. Rec. 2022, 22, e202100310.
37. Li, J.; Qi, Y.; Mei, Y.; Ma, S.; Li, Q.; Xin, B.; Yao, T.; Wu, J. Construction of phosphorus-doped carbon nitride/phosphorus and sulfur co-doped carbon nitride isotype heterojunction and their enhanced photoactivity. J. Colloid Interface Sci. 2020, 566, 495–504.
38. Zhang, B.; Li, X.; Zhao, Y.; Song, H.; Wang, H. Facile synthesis of oxygen doped mesoporous graphitic carbon nitride with high photocatalytic degradation efficiency under simulated solar irradiation. Colloids Surf. A Physicochem. Eng. Asp. 2019, 580, 123736.
39. Jiang, L.; Yuan, X.; Zeng, G.; Liang, J.; Wu, Z.; Wang, H.; Zhang, J.; Xiong, T.; Li, H. A facile band alignment of polymeric carbon nitride isotype heterojunctions for enhanced photocatalytic tetracycline degradation. Environ. Sci. Nano 2018, 5, 2604–2617.
40. Chen, M.; Jia, Y.; Li, H.; Wu, Z.; Huang, T.; Zhang, H. Enhanced pyrocatalysis of the pyroelectric BiFeO3/g-C3N4 heterostructure for dye decomposition driven by cold-hot temperature alternation. J. Adv. Ceram. 2021, 10, 338–346.
41. Zhang, H.; Guo, L.-H.; Zhao, L.; Wan, B.; Yang, Y. Switching oxygen reduction pathway by exfoliating graphitic carbon nitride for enhanced photocatalytic phenol degradation. J. Phys. Chem. Lett. 2015, 6, 958–963.
42. Li, X.; Yu, J.; Jaroniec, M. Hierarchical photocatalysts. Chem. Soc. Rev. 2016, 45, 2603–2636.
43. Liu, Y.; Tian, J.; Wei, L.; Wang, Q.; Wang, C.; Xing, Z.; Li, X.; Yang, W.; Yang, C. Modified g-C3N4/TiO2/CdS ternary heterojunction nanocomposite as highly visible light active photocatalyst originated from CdS as the electron source of TiO2 to accelerate Z-type heterojunction. Sep. Purif. Technol. 2021, 257, 117976.
44. Gao, J.; Wang, Y.; Zhou, S.; Lin, W.; Kong, Y. A facile one-step synthesis of Fe-doped g-C3N4 nanosheets and their improved visible-light photocatalytic performance. ChemCatChem 2017, 9, 1708–1715.
45. Zhang, Y.; Zhou, J.; Feng, Q.; Chen, X.; Hu, Z. Visible light photocatalytic degradation of MB using UiO-66/g-C3N4 heterojunction nanocatalyst. Chemosphere 2018, 212, 523–532.

46. Du, X.; Bai, X.; Xu, L.; Yang, L.; Jin, P. Visible-light activation of persulfate by TiO2/g-C3N4 photocatalyst toward efficient degradation of micropollutants. Chem. Eng. J. 2020, 384, 123245.
47. Khan, I.; Yuan, A.; Khan, S.; Khan, A.; Khan, S.; Shah, S.A.; Luo, M.; Yaseen, W.; Shen, X.; Yaseen, M. Graphitic carbon nitride composites with gold and ZIF-67 nanoparticles as visible-light-promoted catalysts for CO2 conversion and bisphenol A degradation. ACS Appl. Nano Mater. 2022, 5, 13404–13416.
48. Zhou, W.-J.; Ma, L.-X.; Li, L.-Y.; Zha, M.; Li, B.-L.; Wu, B.; Hu, C.-J. Synthesis of a 3D Cu (II) MOF and its heterostructual g-C3N4 composite showing improved visible-light-driven photodegradation of organic dyes. J. Solid State Chem. 2022, 315, 123520.
49. Kumar, O.P.; Ahmad, M.; Nazir, M.A.; Anum, A.; Jamshaid, M.; Shah, S.S.A.; Rehman, A. Strategic combination of metal–organic frameworks and C3N4 for expeditious photocatalytic degradation of dye pollutants. Environ. Sci. Pollut. Res. 2022, 29, 35300–35313.
50. Shekardasht, M.B.; Givianrad, M.H.; Gharbani, P.; Mirjafary, Z.; Mehrizad, A. Preparation of a novel Z-scheme g-C3N4/RGO/Bi2Fe4O9 nanophotocatalyst for degradation of Congo Red dye under visible light. Diam. Relat. Mater. 2020, 109, 108008.
51. Liu, Y.; Shen, Z.; Song, J.; Qi, H.; Yin, C.; Zou, X.; Xia, Q.; Cui, L.; Li, X.; Wang, Y. Honeycomb-like g-C3N4/CeO2-x nanosheets obtained via one step hydrothermal-roasting for efficient and stable Cr (VI) photo-reduction. Chin. Chem. Lett. 2020, 31, 2747–2751.
52. Prabavathi, S.L.; Saravanakumar, K.; Park, C.M.; Muthuraj, V. Photocatalytic degradation of levofloxacin by a novel Sm6WO12/g-C3N4 heterojunction: Performance, mechanism and degradation pathways. Sep. Purif. Technol. 2021, 257, 117985.
53. Deng, Y.; Liu, J.; Huang, Y.; Ma, M.; Liu, K.; Dou, X.; Wang, Z.; Qu, S.; Wang, Z. Engineering the photocatalytic behaviors of g/C3N4-based metal-free materials for degradation of a representative antibiotic. Adv. Funct. Mater. 2020, 30, 2002353.
54. Paul, D.R.; Gautam, S.; Panchal, P.; Nehra, S.P.; Choudhary, P.; Sharma, A. ZnO-modified g-C3N4: A potential photocatalyst for environmental application. ACS Omega 2020, 5, 3828–3838.
55. Wu, L.; Chen, Y.; Li, Y.; Meng, Q.; Duan, T. Functionally integrated g-C3N4@ wood-derived carbon with an orderly interconnected porous structure. Appl. Surf. Sci. 2021, 540, 148440.
56. Farooq, N.; Luque, R.; Hessien, M.M.; Qureshi, A.M.; Sahiba, F.; Nazir, M.A.; Ur Rehman, A. A comparative study of cerium-and ytterbium-based GO/g-C3N4/Fe2O3 composites for electrochemical and photocatalytic applications. Appl. Sci. 2021, 11, 9000.
57. Kumar, O.P.; Shahzad, K.; Nazir, M.A.; Farooq, N.; Malik, M.; Shah, S.S.A.; Ur Rehman, A. Photo-Fenton activated C3N4x/AgOy@ Co1-xBi0. 1-yO7 dual s-scheme heterojunction towards degradation of organic pollutants. Opt. Mater. 2022, 126, 112199.

58. Yassin, J.M.; Taddesse, A.M.; Sánchez-Sánchez, M. Sustainable synthesis of semicrystalline Zr-BDC MOF and heterostructural Ag3PO4/Zr-BDC/g-C3N4 composite for photocatalytic dye degradation. Catal. Today 2022, 390, 162–175.
59. Hasija, V.; Raizada, P.; Sudhaik, A.; Singh, P.; Thakur, V.K.; Khan, A.A.P. Fabrication of Ag/AgI/WO3 heterojunction anchored P and S co-doped graphitic carbon nitride as a dual Z scheme photocatalyst for efficient dye degradation. Solid State Sci. 2020, 100, 106095.
60. Feng, Z.; Zeng, L.; Zhang, Q.; Ge, S.; Zhao, X.; Lin, H.; He, Y. In situ preparation of g-C3N4/Bi4O5I2 complex and its elevated photoactivity in Methyl Orange degradation under visible light. J. Environ. Sci. 2020, 87, 149–162.
61. Zheng, C.-W.; Niu, H.-Y.; Liang, C.; Niu, C.-G.; Zhao, X.-F.; Zhang, L.; Li, J.-S.; Guo, H.; Liu, H.-Y.; Liang, S. A study on advanced oxidation mechanism of MnCo2O4/g-C3N4 degradation of nitrobenzene: Sacrificial oxidation and radical oxidation. Chem. Eng. J. 2021, 403, 126400.
62. Song, T.; Xie, C.; Matras-Postolek, K.; Yang, P. 2D layered g-C3N4/WO3/WS2 S-scheme heterojunctions with enhanced photochemical performance. J. Phys. Chem. C 2021, 125, 19382–19393.
63. Yu, X.; Zhang, X.; Zhao, J.; Xu, L.; Yan, J. Flower-like shaped Bi12TiO20/g-C3N4 heterojunction for effective elimination of organic pollutants: Preparation, characterization, and mechanism study. Appl. Organomet. Chem. 2020, 34, e5702.
64. Feng, S.; Chen, T.; Liu, Z.; Shi, J.; Yue, X.; Li, Y. Z-scheme CdS/CQDs/g-C3N4 composites with visible-near-infrared light response for efficient photocatalytic organic pollutant degradation. Sci. Total Environ. 2020, 704, 135404.
65. Liang, Q.; Liu, X.; Shao, B.; Tang, L.; Liu, Z.; Zhang, W.; Gong, S.; Liu, Y.; He, Q.; Wu, T. Construction of fish-scale tubular carbon nitride-based heterojunction with boosting charge separation in photocatalytic tetracycline degradation and H2O2 production. Chem. Eng. J. 2021, 426, 130831.
66. Huang, Y.; Li, B.; Wu, F.; Yang, B. Fabrication of novel flower-like Co3O4/g-C3N4 heterojunction for tetracycline degradation under visible light irradiation. Mater. Lett. 2022, 311, 131538.
67. Chen, W.; Huang, J.; He, Z.-C.; Ji, X.; Zhang, Y.-F.; Sun, H.-L.; Wang, K.; Su, Z.-W. Accelerated photocatalytic degradation of tetracycline hydrochloride over CuAl2O4/g-C3N4 pn heterojunctions under visible light irradiation. Sep. Purif. Technol. 2021, 277, 119461.
68. Shi, Y.; Li, J.; Wan, D.; Huang, J.; Liu, Y. Peroxymonosulfate-enhanced photocatalysis by carbonyl-modified g-C3N4 for effective degradation of the tetracycline hydrochloride. Sci. Total Environ. 2020, 749, 142313.
69. Luo, J.; Dai, Y.; Xu, X.; Liu, Y.; Yang, S.; He, H.; Sun, C.; Xian, Q. Green and efficient synthesis of Co-MOF-based/g-C3N4 composite catalysts to activate peroxymonosulfate for degradation of the

antidepressant venlafaxine. J. Colloid Interface Sci. 2022, 610, 280–294.

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