

Graphitic carbon nitride meets biomass: a roadmap for designing efficient photocatalysts

Zhaoqiang Wang, Xin Liu, Zihe Chen, Yin Xiao, Li Shuai*, Yonghao Ni*, Guangfu Liao*

College of Materials Engineering, Fujian Agriculture and Forestry University, Fuzhou 350002, China.

ABSTRACT: Graphitic carbon nitride ($g\text{-C}_3\text{N}_4$) has emerged as a promising metal-free polymeric semiconductor with immense transformative potential in solar-driven energy conversion and environmental remediation, underpinned by its thermodynamically favorable band structure for key redox reactions, exceptional chemical and thermal stability, low-cost scalable synthesis, and adjustable visible-light responsiveness. However, its practical industrial exploitation remains severely hampered by three intrinsic bottlenecks: ultrafast recombination of photogenerated electron-hole pairs that drastically reduces quantum efficiency, inadequate visible-light absorption region that limits full-spectrum solar utilization, and a scarcity of active surface sites that restricts overall reaction performance. To overcome these long-standing intrinsic bottlenecks, biomass-based functionalization has emerged as a rapidly growing research frontier, offering a sustainable, low-cost alternative to conventional high-input chemical modification strategies. As the most abundant renewable carbon feedstock on Earth, biomass providing a uniquely versatile and green platform for the rational engineering of $g\text{-C}_3\text{N}_4$. In this review, we systematically summarize state-of-the-art recent advances in biomass-engineered $g\text{-C}_3\text{N}_4$ photocatalysts, elaborate their core regulatory functions and underlying enhancement mechanisms, and provide critical theoretical references for future research in this rapidly evolving field.

KEYWORDS: Biomass, $g\text{-C}_3\text{N}_4$, Photocatalysis, Regulation strategy

Highlights

- Reviews recent progress in biomass-engineered $g\text{-C}_3\text{N}_4$ photocatalysts.
- Clarifies the roles of different biomass components and key regulation strategies.
- Highlights key enhancement mechanisms involving hydrogen-bond networks, vacancy defects and interfacial heterojunctions.
- Reviews representative photocatalytic applications in energy conversion and environmental remediation.
- Proposes future directions toward controllable, durable and sustainable biomass- $g\text{-C}_3\text{N}_4$ systems.

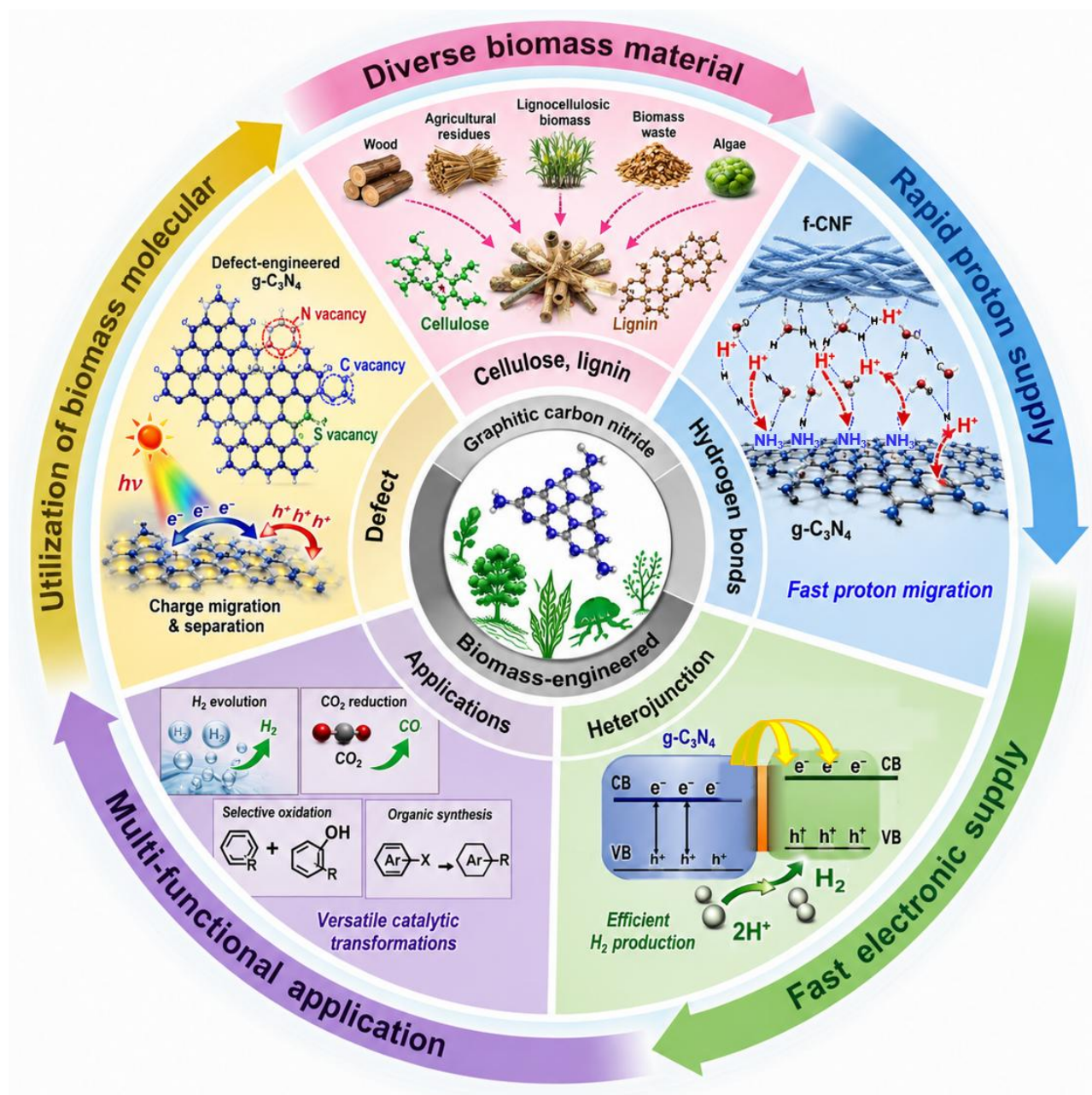
Received: June 18, 2026. **Revised:** July 16, 2026. **Accepted:** July 16, 2026. **Available online:** July 16, 2026

***Corresponding author:** E-mail addresses: lishuai@fafu.edu.cn (S. Li); yonghao@unb.ca (Y. Ni); liaogf@fafu.edu.cn (G. Liao)

© 2026 Wave Academic Press Limited.

This is an open access article under the CC BY-NCND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

Graphical Abstract



In this review, we systematically summarize state-of-the-art recent advances in biomass-engineered $g\text{-C}_3\text{N}_4$ photocatalysts.

1. Introduction

Graphitic carbon nitride ($g\text{-C}_3\text{N}_4$) exhibits great application potential in energy conversion and environmental remediation due to its favorable visible-light response, suitable band structure, high chemical stability, low cost and facile synthesis.^[1-9]

Nevertheless, the deployment of $g\text{-C}_3\text{N}_4$ are severely restricted by fast recombination of photogenerated electron-hole pairs,^[10, 11] insufficient visible-light absorption capacity,^[12-16] and limited number of surface active sites.^[17-21] To overcome these drawbacks, many modification strategies have been developed, among which biomass engineering emerges

as a green, sustainable and highly efficient approach. Biomass, primarily composed of cellulose, hemicellulose and lignin, possesses an inherently hierarchical porous architecture and a rich surface chemistry featuring hydroxyl, aldehyde and carboxyl moieties.^[22] It serves not only as a potential clean energy carrier but also as an ideal precursor for catalytic materials and functional additives.^[23] In 2017, Liu et al.^[24] first pioneered the carbon quantum dot/g-C₃N₄ photocatalytic system and demonstrated excellent synergistic catalytic activity between the two components. Building on this seminal work, Zhang and his co-workers^[25] fabricated biomass-derived carbon quantum dots using orange peel, coupled them with g-C₃N₄ composites, for fluoroquinolone antibiotic degradation. Subsequently, our group systematically investigated the hydrogen-bonding interactions between cellulose and g-C₃N₄ and innovatively proposed the concept of biomass proton donors.^[18, 26] More recently, advances in biomass-derived carbon engineering have further accelerated the high-value valorization of biomass (**Fig. 1**).^[27] Collectively, these foundational studies have established a robust framework for the rational design of high-performance biomass-based photocatalytic systems.

Research advances in biomass-engineered g-C₃N₄ composite photocatalysts have achieved remarkable progress to date.^[2, 28] Diversified design strategies have been successively developed ranging from simple physical blending and covalent bonding construction to morphological regulation and heterojunction fabrication as well as mono-component hybridization and biomass derived carbon nitrogen co-doping modification. These elaborate modification approaches have substantially enhanced the photocatalytic activity and structural stability of g-C₃N₄-based composites toward diverse reaction systems including water splitting for H₂ evolution, H₂O₂ production, CO₂ reduction, and organic pollutant elimination.^[18, 22, 24 -26] Nevertheless, this research field still faces several critical bottlenecks that restrict its further advancement. The inherent complexity and structural variability of natural biomass inevitably trigger structural collapse and the loss of active sites during composite fabrication. Moreover, the interfacial interaction mechanism between biomass substrates and g-C₃N₄ is still poorly understood, and reliable strategies for precisely regulating interfacial electron transfer are currently lacking. Accordingly, the rational design of high-efficiency biomass-engineered g-C₃N₄ photocatalysts remains to be further optimized and refined.

Based on the above background introduction, this review centers on the core theme of constructing high

efficiency photocatalysts through the coupling of graphitic carbon nitride and biomass. It systematically summarizes the design principles, fabrication strategies, performance regulation mechanisms, and representative application advances of biomass-engineered g-C₃N₄. The work further clarifies the fundamental roles of hydrogen bonds engineering, heterojunction engineering, and defect engineering in optimizing light harvesting capacity charge separation behavior and interfacial reaction kinetics of such biomass-engineered materials. It also comprehensively discusses the dominant bottlenecks and key scientific challenges restricting current research progress. Finally, it delivers a forward-looking review on the future development roadmap of biomass-engineered g-C₃N₄ photocatalysts from multiple dimensions. This review aims to provide in depth theoretical references and practical guidelines for the rational design of innovative photocatalytic materials with prominent activity robust stability and favorable environmental compatibility. It also promotes the in-depth integration of advanced photocatalytic technology and high value biomass utilization to facilitate the sustainable development of energy and environmental remediation systems.

2. Synthesis strategies of g-C₃N₄

Various synthetic strategies for graphite nitride carbon (g-C₃N₄) nanosheets could endow the material with distinctive microstructures, electronic properties and surface features. At present, all synthetic pathways for nanostructured g-C₃N₄ can be generally grouped into two fundamental strategies, top-down and bottom-up strategies. Top-down strategies employ external driving forces to overcome interlayer van der Waals forces within bulk g-C₃N₄, yielding monolayer and few-layer nanosheets. Benefiting from simple operation and well-retained intrinsic crystal frameworks, representative techniques cover liquid exfoliation and thermal exfoliation. Bottom-up strategies depend on the polymerization and self-assembly of molecular precursors to precisely modulate the growth of g-C₃N₄ nanostructures at the atomic level, enabling fine regulation of their morphology, pore architecture and electronic configuration. The most widely adopted methods include solvothermal synthesis, supramolecular preassembly and templating routes.

2.1 Top-down strategies

Top-down synthetic strategies leverage diverse external driving forces to exfoliate and thicken bulk-

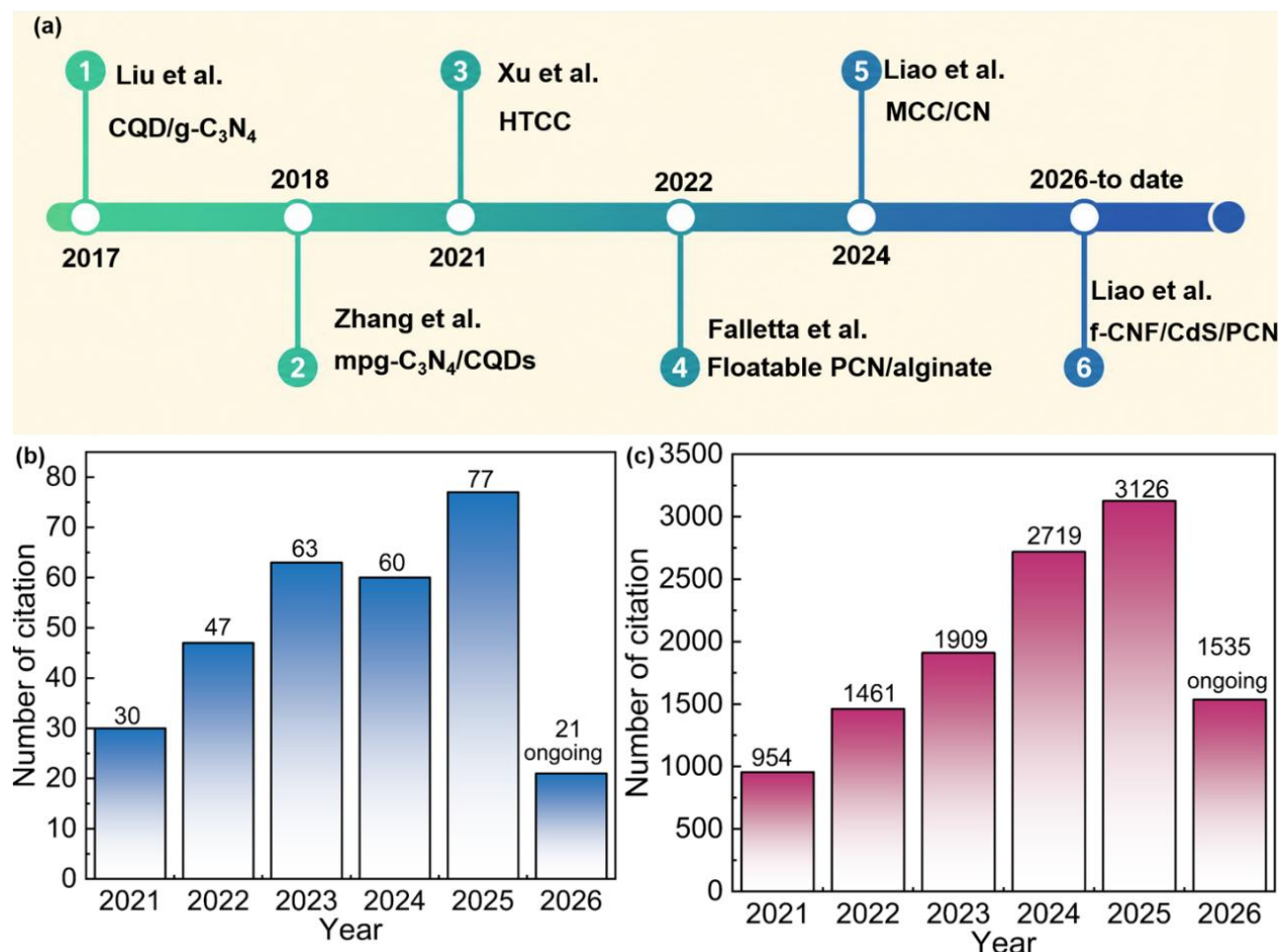


Fig. 1 (a) Evolutionary trajectory of biomass-engineered photocatalysis. [24, 25], [18, 26, 29-35] The development and statistics of photocatalysis in biomass-engineered: (b) The number of publications between 2021 and 2026. (c) The number of citations each year. (The data for analysis of the development of photocatalysis in biomass-engineered was retrieved up to 3th July 2026 from all databases when “biomass *” and “photocatalysts” were incorporated as the topic). [30, 34, 36, 37]

layered g-C₃N₄ into small-sized porous carbon nitride (PCN) particles. Rational top-down engineering can disrupt the internal hydrogen bonding and van der Waals stacking interactions of bulk g-C₃N₄ (BCN), substantially boosting the specific surface area and dispersibility of the material in reaction media. To date, the predominant top-down approaches for converting BCN into PCN include chemical exfoliation, liquid exfoliation and thermal exfoliation. This section systematically elaborates the applications of these methodologies in the application of PCN.

2.1.1 Chemical exfoliation technique

Chemical exfoliation is a relatively mature and efficient top-Down Strategies for preparing ultrathin two-dimensional (2D) g-C₃N₄ nanosheets. This

technique relies on intercalation of acid/base ions or oxidative species into bulk g-C₃N₄ interlayers to disrupt interlayer hydrogen bonds and π - π van der Waals stacking, combined with mild etching and surface functionalization to delaminate stacked sheets.^[38] Liang *et al.*^[39] successfully fabricate bromine-doped carbon nitride (BrCN) nanosheets via a chemical exfoliation strategy, enabling the construction of high-loading and long-cycle-stable zinc-iodine batteries (**Fig. 2a-d**). Compared with pristine carbon nitride, the resultant BrCN nanosheets exhibit optimized structural characteristics and substantially enlarged specific surface area. In another related study, Wang *et al.*^[40] reported carboxylation-acylation chemical exfoliation strategy to synthesize amino-modified CN with adjustable adsorption functional groups. These

treatments retained CN crystal structures, exfoliated bulk CN into non-aggregated thin nanosheets, and introduced abundant ethylenediamine-derived $-NH_2$ sites on 24-CN-EDA. The controllable amino decoration via EDA functionalization greatly enhanced the photocatalytic activity of CN. Additionally, Feng *et al.* [38] developed a nitrate intercalation and decomposition (NID) strategy for the chemical exfoliation of bulk carbon nitride (**Fig. 2e-i**). This approach integrates dilute nitric acid-mediated hydrothermal pretreatment with temperature-controlled

pyrolysis, enabling the controllable exfoliation of bulk g-CN (BCN). The method affords few-layer g-CN with tunable layer thickness and permits the precise fabrication of bilayer g-CN samples. Compared with exfoliation systems employing phosphoric acid or concentrated sulfuric acid, the NID strategy avoids residual impurity contamination. Moreover, dilute nitric acid can in situ introduce oxygen-containing functional groups, which remodels the surface microstructure of g- C_3N_4 , further boosting its oxygen adsorption capacity and catalytic kinetic performance (**Fig. 2j-k**).

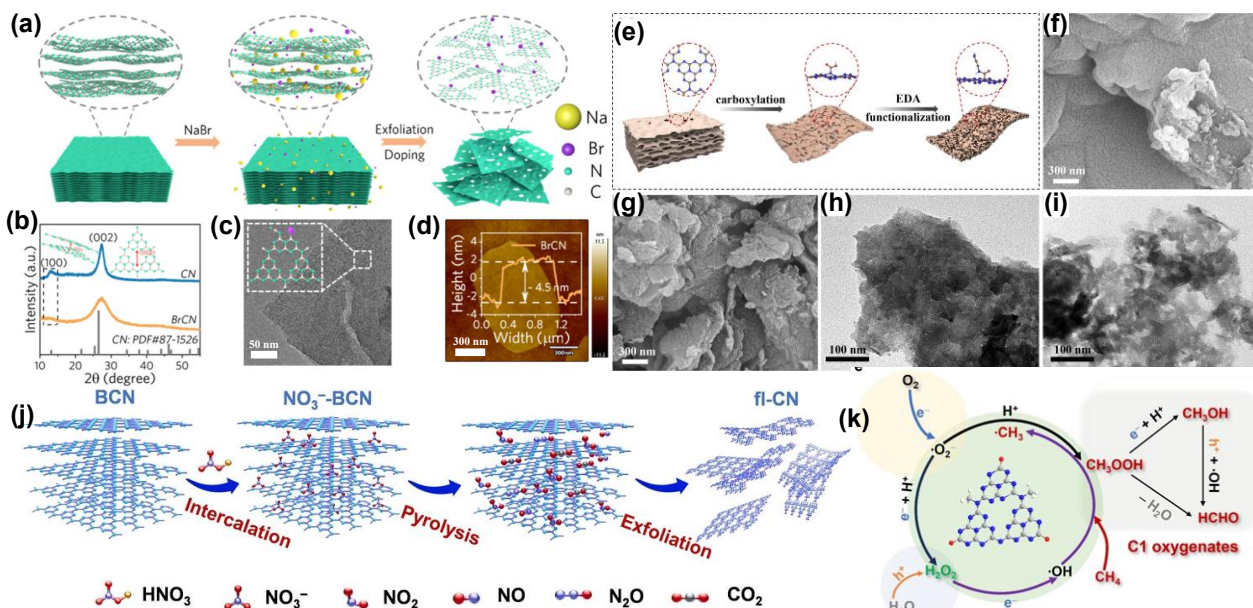


Fig. 2 (a) Characterizations of BrCN host materials. (b) XRD profiles of BrCN and CN. (c) TEM image of BrCN, with the molecular structure shown in the inset. (d) AFM results of BrCN and corresponding height profile. Reproduced from ref. [39] (e) Synthesis scheme of X-CN-EDA. (f) SEM image of bulk CN, (g) SEM image of 24-CN-EDA, (h) TEM image of bulk CN, and (i) TEM image of 24-CN-EDA. Reproduced from ref. [40] (j) Schematic illustration of the nitrate anion intercalation-decomposition (NID) strategy for the exfoliation of BCN into few-layered C_3N_4 (fl-CN). (k) The plausible mechanism for photocatalytic oxidation of CH_4 with O_2 to C1 oxygenates over fl-CN-530. Reproduced from ref. [38]

2.1.2 liquid exfoliation technique

Liquid exfoliation technique has been validated as a pivotal synthetic strategy for fabricating size-tunable g- C_3N_4 nanostructures. When dispersed in appropriate solvents, solvent molecules interact with g- C_3N_4 via intermolecular forces and intercalate uniformly between adjacent layers. In the work reported by Zhou *et al.* [41], bulk yellow g- C_3N_4 was first synthesized through conventional thermal polymerization, followed by liquid-phase exfoliation in N-methylpyrrolidone (NMP) to obtain few-layer g- C_3N_4 nanosheets (**Fig. 3a**). Alternatively, Wang *et al.* [42] prepared layered poly (triazine imide) (PTI) via an ionothermal method, which was further subjected to one-step liquid

exfoliation in water to yield 2D carbon nitride nanosheets. The as-obtained triazine-based nanosheets possess a thickness ranging from 1 to 2 nm and can form stable suspensions under both acidic and alkaline environments (**Fig. 3b-d**).

2.1.3 Thermal exfoliation approach

Thermal oxidation is an effective route to exfoliate graphite into monolayer graphene or large-area graphene sheets. Owing to the structural resemblance between g- C_3N_4 and graphene, this approach has also been explored for the fabrication of g- C_3N_4 nanosheets. By modulating the microstructure of bulk pristine g- C_3N_4 (BCN) through thermal and ultrasonic exfoliation, Zheng *et al.* [43] successfully synthesized porous

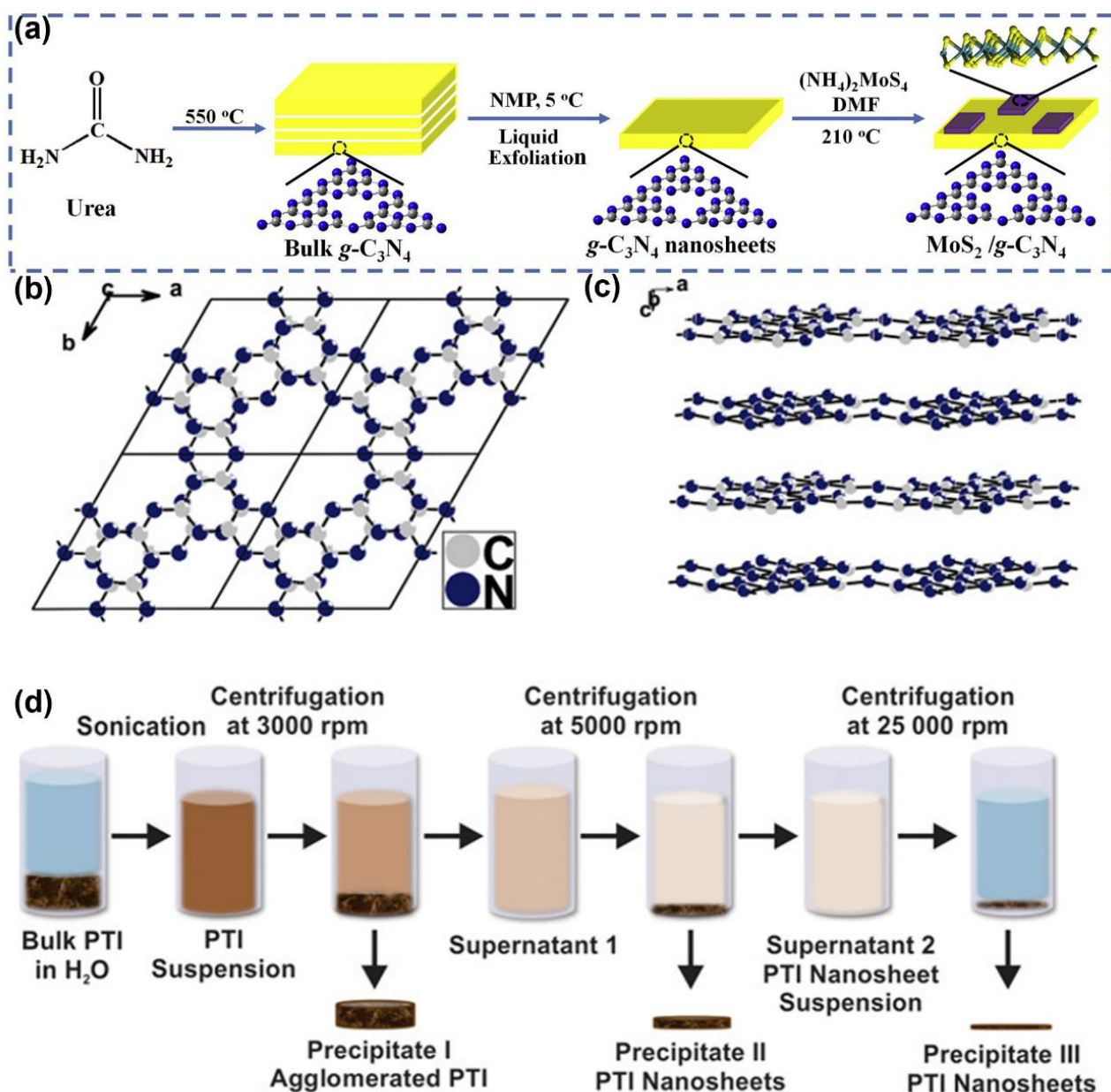


Fig. 3 (a) Schematic diagram of the synthesis of MoS₂/g-C₃N₄ nanosheets photocatalysts. Reproduced from ref.^[41] (b) Idealized PTI structure (lithium/chloride intercalation omitted for clarity) viewed along the c-axis and the slightly tilted b-axis (c). (d) Scheme of the exfoliation process and product labeling. Reproduced from ref.^[42]

ultrathin g-C₃N₄ nanosheets (PuCN), which possessed plenty of anchoring sites to facilitate single-atom loading. (Fig. 4a) Wu *et al.*^[44] prepared bulk carbon nitride (Bulk-CN) using low-cost dicyandiamide as the precursor, and successfully transformed it into three types of carbon nitride nanosheets (CNNs) via a facile continuous thermal exfoliation process in air (Fig. 4b). TEM characterizations verified the transformation of

bulk polymeric carbon nitride (PCN) into a 2D layered structure (Fig. 4c). AFM images further provided solid evidence of the successful exfoliation of Bulk-CN into atomically thin nanosheets (Fig. 4d). XRD pattern analysis revealed that the thermal-induced etching effect reduced the in-plane grain size of the material, while the planarization of wrinkled monolayers during heat treatment alleviated the interlayer stacking of the

Bulk-CN structure (**Fig. 4e**). Although the conventional thermal exfoliation method can enlarge the specific surface area of g-C₃N₄, it inevitably aggravates the incomplete polymerization of heptazine molecular chains. To address this issue, Jia *et al.* [45] developed a thermal repolymerization strategy under nitrogen atmosphere to repair the defective structure of CN and synthesize bulk g-C₃N₄ with highly polymerized heptazine chains (NCN) (**Fig. 4f**). Specifically, bulk g-C₃N₄ with incompletely polymerized structures (CN) derived from urea thermal polymerization was first exfoliated into ultrathin porous nanosheets with a high specific surface area (ACN) via thermal shearing in an ammonia atmosphere. Subsequent thermal repolymerization between amino groups further precisely repaired the broken heptazine chains of ACN, ultimately yielding ultrathin porous g-C₃N₄ nanosheets (NACN) that integrate high specific surface area and highly polymerized heptazine chains. AFM characterization verified that the obtained NACN

presents an ultrathin porous nanosheet structure with a thickness of 1.5 nm after thermal shearing treatment (**Fig. 4g**). In a recent study, Zhang and co-workers synthesized ultrathin g-C₃N₄ nanosheets through a strategy integrating synergistic thermal exfoliation and ultrasonic exfoliation. [45] Attributed to the ultrathin structural characteristic, the nanosheet substrate enables the firm anchoring of AuPt nanoparticles by electrostatic adsorption coupled with in-situ NaBH₄ reduction, thereby tuning the electronic structure and greatly promoting the photocatalytic performance of the composite catalyst. Collectively, combined with auxiliary ultrasonic treatment or post thermal repolymerization engineering, thermal exfoliation approach not only effectively mitigates severe interlayer stacking of bulk carbon nitride but also provides a scalable platform for loading metal nanoparticles or single atoms, holding great promise for developing high-efficiency carbon nitride-based photocatalytic materials.

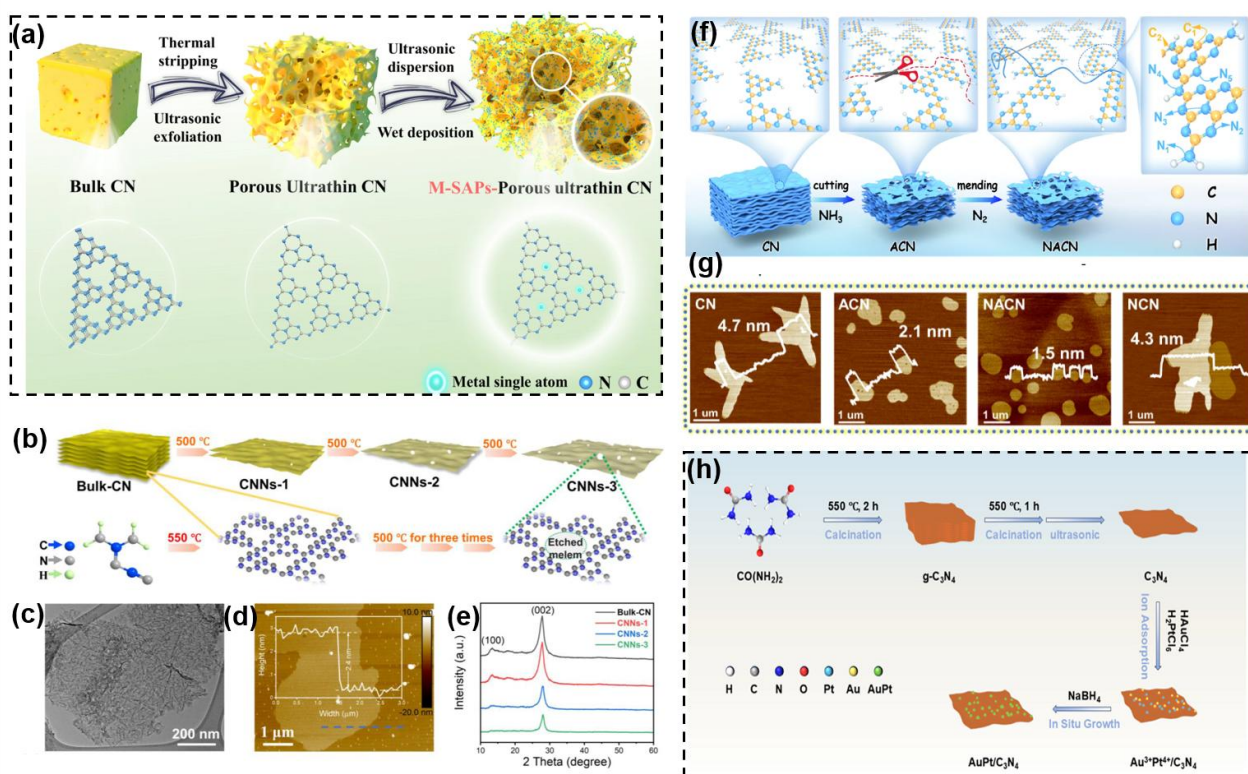


Fig. 4 (a) Schematic diagram of the synthesis of high-loading M-SAPs-PuCN. (b) XRD profiles of BrCN and CN. Reproduced from ref. [43]. (b) Procedure of preparing CNNs. (c) TEM of CNNs-3. (d) AFM of CNNs-3 with height profile inset. (e) XRD of CNNs. Reproduced from ref. [44]. (f) Schematic illustration of the synthesis process of photocatalysts. (g) AFM images of prepared samples. Reproduced from ref. [46]. (h) Synthesis and characterization of AuPt/C₃N₄. Reproduced from ref. [45].

2.2 Bottom-up strategies

Bottom-up methodologies underpin g-C₃N₄ synthesis

by enabling the direct conversion of nitrogen-containing precursors into polymeric g-C₃N₄. As documented in previous studies, such synthetic routes

preserve the intrinsic backbone of g-C₃N₄ to the greatest extent, suppress the formation of undesired defect sites, and thereby facilitate the separation of photogenerated charge carriers. To date, the predominant top-down approaches include solvothermal synthesis, supramolecular preassembly and template-mediated approach. This section systematically elaborates the applications of these methodologies in the application of g-C₃N₄.

2.2.1 Solvothermal synthesis

Solvothermal synthesis g-C₃N₄ typically adopts sealed autoclaves with anhydrous organic solvents such as acetonitrile and toluene under mild high-temperature and high-pressure conditions. Different from the traditional thermal polycondensation via direct calcination, this method can precisely regulate the microstructure, defect distribution and crystallinity of carbon nitride by adjusting precursors, reaction temperature, holding time and solvent types. A previous study reported a supercritical methanol (ScMeOH) post-treatment strategy conducted at 250-300 °C under 8.1-11.8 MPa to modulate the structural properties of pristine g-C₃N₄ derived from the thermal polycondensation of melamine (**Fig. 5a**).^[47] During the ScMeOH post-treatment, methanol molecules diffuse into the interlayer spacing of g-C₃N₄ and subsequently trigger intralayer N-methylation and hydroxylation reactions, partially converting pristine g-C₃N₄ into quinonoid poly(heptazine imide)-based carbon nitride (Q-PHI) abundant in methyl and hydroxyl groups (**Fig. 5b**). Molecular dynamics simulations verify that the transformation from g-C₃N₄ to Q-PHI via ScMeOH treatment is thermodynamically spontaneous, and high temperature and high pressure enable more methanol molecules to surmount the kinetic energy barrier for interfacial reaction (**Fig. 5c**). Solution thermal modification strategy can effectively regulate the optoelectronic and excitonic behaviors of carbon nitride. This treatment can efficiently suppress the Coulomb interaction of singlet Frenkel excitons, narrow the band gap of carbon nitride, and thereby inhibit the exciton dissociation process. In a representative modification study, Lu *et al.*^[48] employed a solvothermal protocol to simultaneously introduce π -electron-rich domains and polarizable hydroxyl groups into mesoporous carbon nitride, successfully fabricating ultrathin mesoporous carbon nitride nanosheets (**Fig. 5d**). This work demonstrates that precise functionalization of carbon nitride with diverse functional moieties can rationally tailor its structural and electronic characteristics, ultimately enabling the substantial enhancement of photocatalytic performance.

2.2.2 Supramolecular assembly

Supramolecular assembly of carbon nitride usually employs melamine and cyanuric acid as building blocks to fabricate well-ordered co-crystalline precursors via hydrogen bonding and π - π stacking interactions. Subsequent thermal polycondensation transfers the topological features of these precursors into the final graphitic carbon nitride framework. This strategy enables precise modulation of pore architecture, homogeneous heteroatom doping and controllable defect engineering. The resulting materials possess enlarged specific surface areas, optimized band structures and accelerated separation of photogenerated charge carriers, thereby delivering substantially enhanced photocatalytic activity. Quan's team incorporated uracil into the supramolecular self-assembly system of carbon nitride to precisely regulate carbon doping in the matrix (**Fig. 6a**).^[49] By modulating the electronic structure and dipole moment, a locally asymmetric carbon nitride photocatalyst (KCCNV) with cyano-based electron traps was fabricated. The cyano-group-induced localized electron-rich domains efficiently capture photogenerated electrons and steer directional charge migration, thereby effectively suppressing the non-radiative recombination of photogenerated electron-hole pairs. Li *et al.*^[50] developed a fluid shear force-assisted supramolecular self-assembly strategy to disrupt the stacked layered structure of bulk carbon nitride, yielding carbon nitride clusters assembled from ultrathin nanosheets (**Fig. 6b**). Carbonyl groups and nitrogen vacancies were simultaneously introduced into the conjugated framework of the obtained ASCN. This facile, reagent-free and high-yielding strategy enables the synchronous modulation of the band structure, electronic configuration and morphology of g-C₃N₄. Panangattu *et al.*^[51] achieved molecular-level control over supramolecular complexes self-assembled from cyanuric acid and 3-amino-1, 2, 4-triazole (AT) monomers, verifying that this strategy can be extended to directly regulate crystal growth toward specific phases (**Fig. 6c**). **Figure 6d-f** display distinct morphologies of the as-formed complexes prepared at various molar ratios. Such morphological evolution originates from variations in the hydrogen-bonding environment between the precursor monomers CA and AT.

2.2.3 Template-mediated approach

Template-mediated approach of carbon nitride can be categorized into hard-template and soft-template strategies. Utilizing the spatial confinement effect of templates, nitrogen-containing precursors such as urea and melamine are infiltrated into the pore channels or

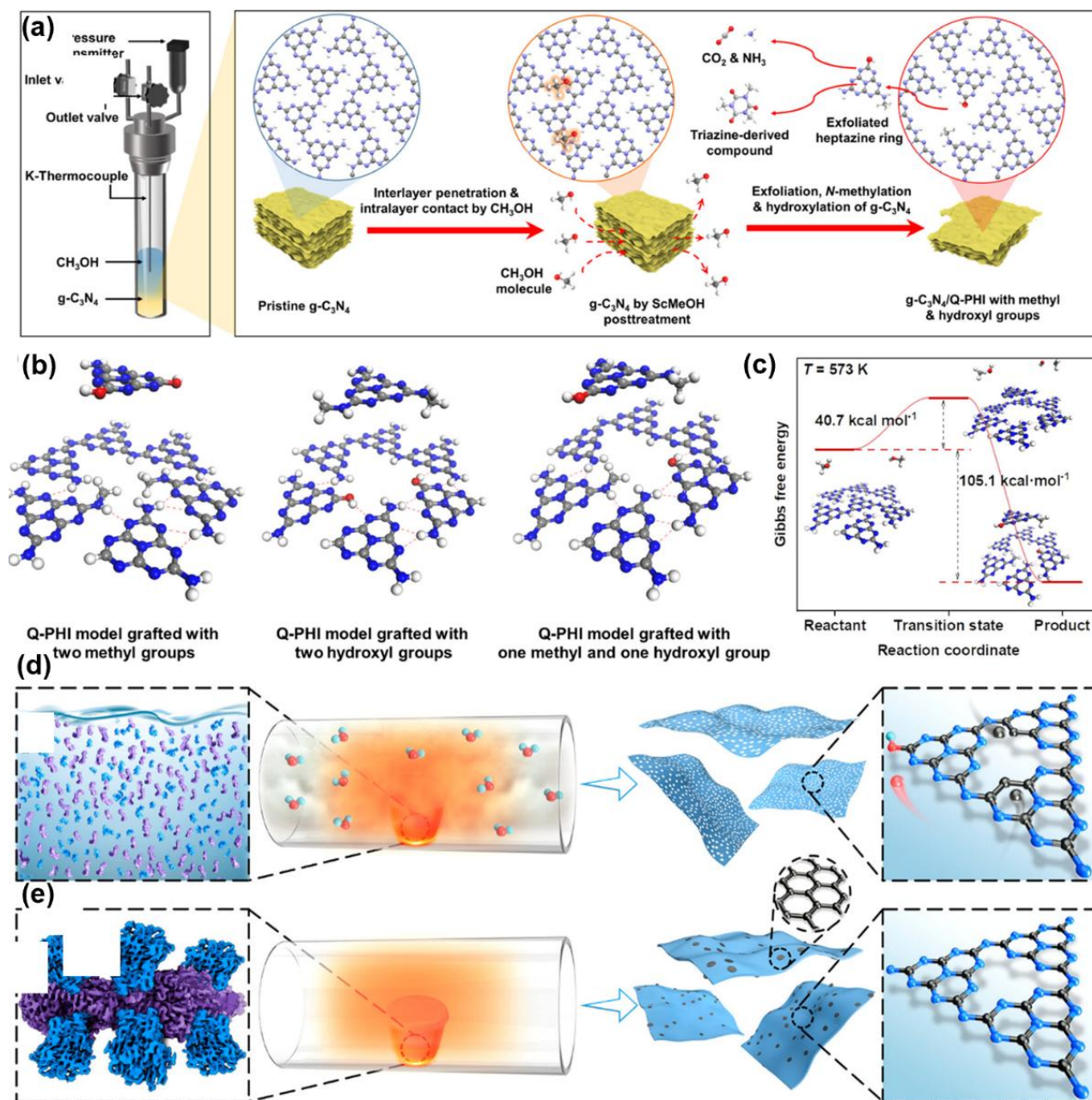


Fig. 5 (a) Schematic illustration of the structural evolution of g-C₃N₄ by the ScMeOH post-treatment. (b) Three kinds of Q-PHI models with different groups and the corresponding exfoliated units. (c) Gibbs free energies calculated by molecular dynamics simulations for the formation pathways of Q-PHI with one methyl and one hydroxyl group. Reproduced from ref.^[47] (d) Schematic illustration of synthesizing modified carbon nitride samples via solution thermal shock. (e) Schematic illustration of synthesizing a carbon nitride sample via the conventional method. Reproduced from ref.^[42]

assembled architectures of templates, followed by high-temperature calcination for thermal polymerization. Subsequent template removal via etching or solvent treatment enables the precise construction of carbon nitride with hierarchical porous morphologies including ordered mesopores, one-dimensional tubular structures

and nanosheets. This approach effectively addresses the drawbacks of bulk carbon nitride, such as severe material stacking, low specific surface area and rapid recombination of photogenerated charge carriers, thereby greatly enhancing light harvesting capacity as well as the separation and transport efficiency of

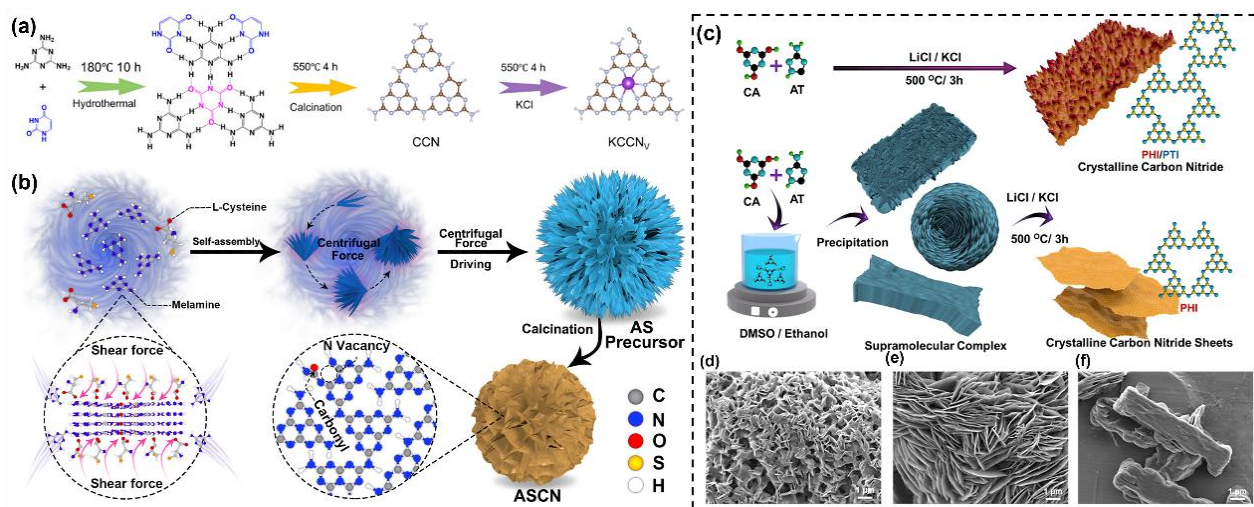


Fig. 6 (a) The synthesis process of KCCN_v. Reproduced from ref. [49] (b) Schematic diagram of the preparation of ASCN. Reproduced from ref. [50] (c) Schematic illustration of the synthesis process of SSCN with PHI structure. Images of supramolecular complexes prepared with different ratios of AT and CA (d) CAT21-P, (e) CAT22-P, and (f) CAT23-P. Reproduced from ref. [51]

photogenerated charges. In the hard template method, Sadanandan *et al.* [52] developed a thermal polymerization strategy employing 3-amino-1, 2, 4-triazole as the nitrogen precursor, sulfur powder as the functionalization agent, and silica nanoparticles as the hard template, successfully fabricating modified carbon nitride catalysts with high specific surface area and tailored surface chemical properties (Fig. 7a-c). Brito and coworkers synthesized copper-incorporated mesoporous carbon nitride (x-Cu-mCN) using mesoporous SBA-15 silica as a hard template (Fig. 7d). [53] Low-angle X-ray diffraction and transmission electron microscopy characterizations verified the well-defined periodic hexagonal porous architecture of the as-synthesized materials. In the soft template method, Zhen's group reported the fabrication of N-doped porous carbon (NPC) with a hierarchical porous structure via high-temperature calcination and chemical activation, where carbon nitride served as both the nitrogen source and structural template, and glucose acted as the carbon precursor (Fig. 7e). [54] The systematic investigation revealed the significant dependence of the specific surface area, nitrogen doping configuration, and electrochemical performance of the resultant NPC materials on the mass ratio of carbon nitride to glucose. Optimally, the NPC sample prepared at a carbon nitride-to-glucose mass ratio of 1:2 (NPC-2) delivered a maximum specific surface area of 2407 mg. Furthermore, Sun *et al.* proposed a moderate- and low-temperature hydrogen thermal treatment strategy for porous carbon nitride, which enabled the directional deposition of in-situ generated

methane on the boundary active sites within the confined porous space, thereby constructing atomic-layer graphene patches on porous carbon nitride (Fig. 7f). [55] The fabricated intra-layer heterostructures effectively reduce the interfacial transport resistance of photogenerated charge carriers. Coupled with the enhanced interfacial electric field effect between graphene and carbon nitride, this structural and compositional modulation synchronously boosts the photocatalytic oxidation and reduction capabilities of the composite photocatalysts.

Both top-down and bottom-up construction strategies possess distinct intrinsic advantages as well as unavoidable limitations. Accordingly, the optimal synthetic strategy should be selected based on specific application scenarios and available resource conditions. In the field of photocatalysis, g-C₃N₄ typically suffers from inherent structural defects including insufficient polymerization degree and poor crystallinity. These drawbacks inevitably lead to sparse active sites, rapid recombination of photogenerated electron-hole pairs, and low visible-light utilization efficiency, which severely restrict the photocatalytic performance of g-C₃N₄. In this regard, structural engineering modification of g-C₃N₄ is highly necessary and imperative for advancing its photocatalytic applications.

3. Biomass-engineered g-C₃N₄

Biomass engineering harnesses the unique structural and chemical characteristics of diverse biomass species

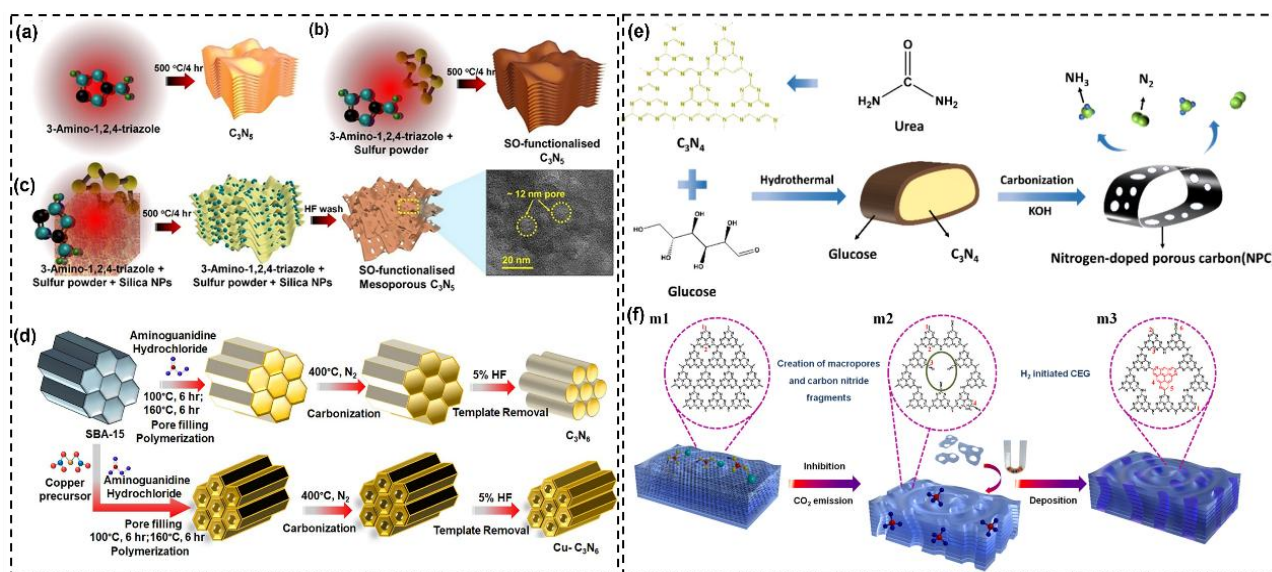


Fig. 7 (a) Schematic diagram of the synthetic protocols for C_3N_4 , (b) Schematic diagram of the synthetic protocols for S- C_3N_4 , (c) Schematic diagram of the synthetic protocols for 5- MSC_3N_4 . Reproduced from ref.^[52] (d) Schematic diagram of the Fabrication of (a) mC_3N_4 and Cu-loaded C_3N_4 nanocomposite. Reproduced from ref.^[53] (e) Schematic representation of the preparation of the NPC. Reproduced from ref.^[54] (f) Schematic illustration of the formation processes of intralayer heterojunctions. m1, m2, and m3 are the proposed molecular structures of g- C_3N_4 , porous carbon nitride, and hydrogenated carbon nitride, respectively. Reproduced from ref.^[55]

to rationally tailor the electronic structure, interfacial interaction, surface morphology, and defect structure of g- C_3N_4 , aiming to significantly enhance its photocatalytic performance.^[56, 57] Different biomass components exhibit distinct functional advantages and regulation mechanisms. For example, cellulose is rich in hydroxyl groups and can form strong hydrogen-bond networks with g- C_3N_4 to accelerate interfacial charge transfer; lignin contains aromatic conjugated structures and phenolic hydroxyl groups, which can construct donor-acceptor systems and promote proton-coupled electron transfer; nitrogen-rich biomass such as chitosan can serve as both nitrogen sources and soft templates to realize in-situ doping and porous structure construction; biomass-derived carbon can act as an electron mediator to build high-speed charge-transport channels. Meanwhile, various biomass can also induce carbon doping, nitrogen vacancies, and hierarchical pore structures to optimize active sites and light-harvesting capacity. In this section, we systematically classify modification strategies based on typical biomass components, clarify the interfacial interaction and electronic regulation mechanisms of different biomass units, and elucidate the specific roles of biomass-based modifications in boosting charge separation, light absorption, and surface catalytic reactivity of g- C_3N_4 .

3.1 Cellulose-engineered g- C_3N_4

Cellulose and its derivatives bear a high density of hydroxyl groups (-OH) along their molecular chains, which form dense, stable intermolecular hydrogen-bonding networks with the amino (-NH₂) groups exposed on the surface and edge sites of g- C_3N_4 .^[18] These interfacial interactions effectively reduce charge-transfer resistance, optimize band alignment, and build robust directional charge-transport pathways. The well-connected interface accelerates photogenerated carrier separation and migration, suppresses electron-hole recombination, extends carrier lifetime, and ultimately enhances the quantum efficiency and photocatalytic performance of the composite. For example, Xiao and co-workers^[58] demonstrated that introducing a small amount of cellulose-based carbon nanofibers (CF) into g- C_3N_4 homojunctions serves as an electron mediator and band-structure regulator, suppressing the recombination of photogenerated electron-hole pairs and enhancing photocatalytic H_2O_2 production (Fig. 8a). Further investigations revealed that the hydrogen-bonding strength between carboxymethyl cellulose (CMC) and g- C_3N_4 increases significantly with a decreasing degree of substitution.^[23] CMC with a low degree of substitution (CMC-L) forms stronger

hydrogen bonds, thereby efficiently boosting interfacial charge transfer. Peng and co-workers^[59] employed cellulose nanofibrils (CNF) as both a modifier and soft template to construct one-dimensional porous g-C₃N₄ nanorods (HCN) with nitrogen vacancies and oxygen doping via hydrogen-bonding assembly and molecular shearing. (Fig. 8b) The optimized HCN catalyst exhibited excellent photocatalytic performance toward biomass monosaccharide oxidation to lactic acid with a yield of 75.5% and a hydrogen production rate of 2.8 mmol h⁻¹ g⁻¹, together with good substrate compatibility and cycling stability. Mechanistic studies and theoretical calculations verified that the synergistic effect of nitrogen vacancies and oxygen doping accelerated the generation of superoxide radicals, which dominated the superior photocatalytic activity. This work provides a green and feasible route for designing high-efficiency photocatalysts applied in biomass refining. Additionally, Liu and co-workers^[60] developed a

highly compressible, ultralight 3D CNF/rGO/g-C₃N₄ aerogel via a facile bidirectional freeze-casting and thermal reduction route, addressing the long-standing trade-off between mechanical stability, recyclability and photocatalytic performance of bulk g-C₃N₄. In this 3D framework, CNFs acted as a reinforcing skeleton via hydrogen-bonding interactions with rGO and g-C₃N₄, endowing the aerogel with excellent mechanical robustness (over 89% height retention after 100 compression cycles at 40% strain), while rGO served as an electron transport channel to accelerate photogenerated carrier separation. The interconnected porous structure fully exposed the active sites of g-C₃N₄, enabling 87.3% RhB degradation efficiency under visible light and a hydrogen evolution rate of 417.5 μmol·h⁻¹·g⁻¹. The monolithic aerogel can be easily recycled with outstanding cyclic stability, providing a practical strategy for fabricating robust, multifunctional 3D g-C₃N₄-based photocatalysts for wastewater treatment and clean energy production.

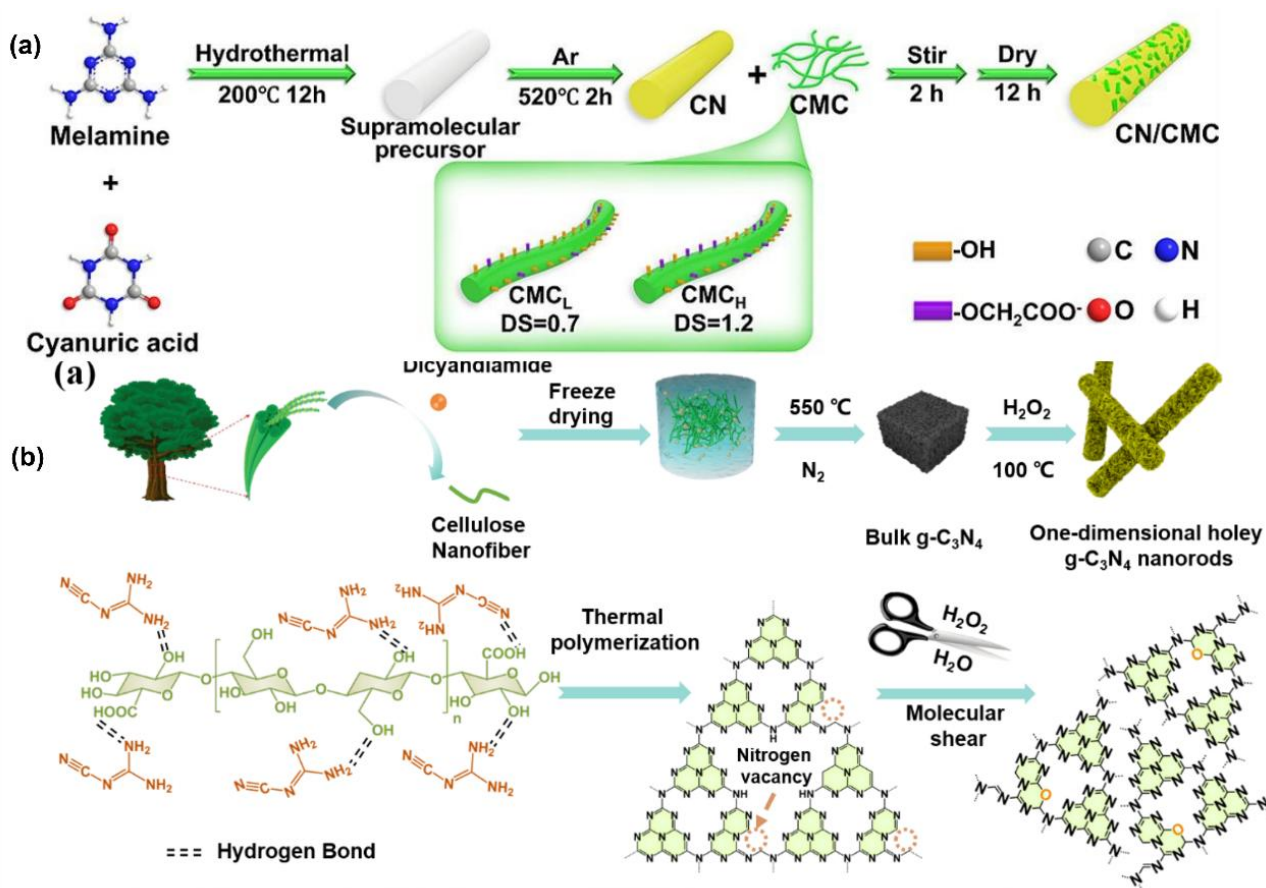


Fig. 8 (a) Schematics of the synthesis process of CN/CMC composites. Reproduced from ref.^[15] (b) Preparation of CNF derived carbon nitride based photocatalyst (HCN). Reproduced from ref.^[59, 60]

3.2 Lignin-engineered g-C₃N₄

Lignin is one of the three core components of lignocellulosic biomass and the only naturally occurring aromatic biopolymer, stands out as a highly promising renewable carbon resource and sustainable alternative to fossil-derived carbon sources, owing to its ultrahigh natural abundance, low cost, and high intrinsic carbon content.^[22, 61] For g-C₃N₄, carbon doping is a well-established, powerful strategy to address its intrinsic performance bottlenecks.^[62] As an earth-abundant, eco-friendly non-metal with an atomic size well-matched to the C/N atoms in the g-C₃N₄ framework, low ionization energy, and high structural stability, carbon is an ideal heteroatom for bulk doping of g-C₃N₄. Incorporating carbon into the g-C₃N₄ conjugated skeleton broadens the visible-light response window, improves intrinsic electronic conductivity, and facilitates photogenerated charge carrier separation and migration through electron trap engineering, thus fundamentally alleviating the key intrinsic limitation of fast electron-hole recombination in pristine g-C₃N₄.^[22] For example, biochar from lignin pyrolysis can introduce abundant bridging C sites and controllable N vacancies into the g-C₃N₄ lattice.^[27] These defect sites finely regulate the local electronic structure, optimize charge density distribution, and lower the energy barrier for C-C coupling during catalytic reactions. Benefiting from these synergistic effects, the lignin-engineered g-C₃N₄ photocatalyst achieves highly selective CO₂ reduction toward C₂H₆, with an outstanding product selectivity of 80.33%. Additionally, Xu and co-workers^[63] fabricated lignin-derived carbon-doped g-C₃N₄ via a facile one-step thermal copolymerization method with lignin as the renewable carbon source, achieving markedly improved photocatalytic performance. Comprehensive characterizations verified that lignin incorporation did not alter the intrinsic heptazine framework of g-C₃N₄, while the optimized LCN-1 sample showed enhanced visible-light absorption and more efficient charge separation and transfer compared with pristine MCN (**Fig. 9a**). The composite delivered outstanding performance in both direct and peroxymonosulfate (PMS)-assisted photocatalytic tetracycline (TC) degradation, as PMS scavenged photogenerated electrons to suppress carrier recombination and boost reactive oxygen species (ROS) generation. This work provides valuable guidance for the construction of low-cost lignin-derived carbon-doped g-C₃N₄, and validates its excellent efficiency in PMS activation-coupled photocatalytic pollutant degradation. Additionally, Zhao and co-workers^[64] used alkali lignin (AL) as a

green carbon precursor to construct porous coral-like g-C₃N₄ with nitrogen vacancies and biochar persistent free radicals (PFRs) for photothermal conversion of 5-hydroxymethylfurfural (HMF) to maleic acid (MA) (**Fig. 9b**). The optimized 1.5% PLCN delivered a maximum MA yield of 50.43% under visible-light irradiation at 90°C for 4 h. Alkali lignin played a critical dual role in forming the biochar component and introducing nitrogen vacancies, which greatly boosted in-situ H₂O₂ production (156.68 μmol L⁻¹ h⁻¹) (**Fig. 9c-e**). Mechanistic studies showed that biochar PFRs induced ·OH generation via a metal-free Fenton-like reaction and provided active sites for ¹O₂ formation, which dominated the selective production of MA. These work offers new strategies for lignin valorization and the design of multifunctional g-C₃N₄ photocatalysts for selective biomass conversion.

3.3 Biomass-derived carbon-engineered g-C₃N₄

Biomass-derived carbon engineering serves as a green and powerful strategy to optimize g-C₃N₄, where various biomass precursors can be converted into functional carbon materials via controlled pyrolysis, acting as high-speed electron mediators to construct π-π conjugated heterojunctions with g-C₃N₄, significantly accelerating the separation and migration of photogenerated carriers and suppressing electron-hole pair recombination. Meanwhile, the thermal decomposition of biomass introduces abundant hierarchical porous structures, carbon doping and nitrogen vacancies into g-C₃N₄, which broaden the visible-light absorption range, increase specific surface area and surface active sites, optimize the local electronic structure and reduce the reaction energy barrier of key intermediates, thereby comprehensively enhancing the photocatalytic performance of g-C₃N₄ in hydrogen evolution, H₂O₂ production, CO₂ reduction and pollutant degradation, and realizing the high-value utilization of biomass resources synchronously. A *et al.*^[65] used hemp stalks as the renewable carbon precursor and prepared defect-enriched Ag₃BiO₃/ZnO/BC composites by hydrothermal treatment. The in-situ formed n-n heterojunction and incorporated biochar exert a synergistic effect, which effectively promotes the separation and migration of photogenerated electron-hole pairs and suppresses charge recombination. After compositional optimization, the optimal sample, 0.2-Ag₃BiO₃/ZnO/BC, exhibits excellent photocatalytic activity and stability, achieving a 95.8% removal efficiency of levofloxacin (LFX) within 120 minutes. Primitive g-C₃N₄ suffers from large exciton binding energy and

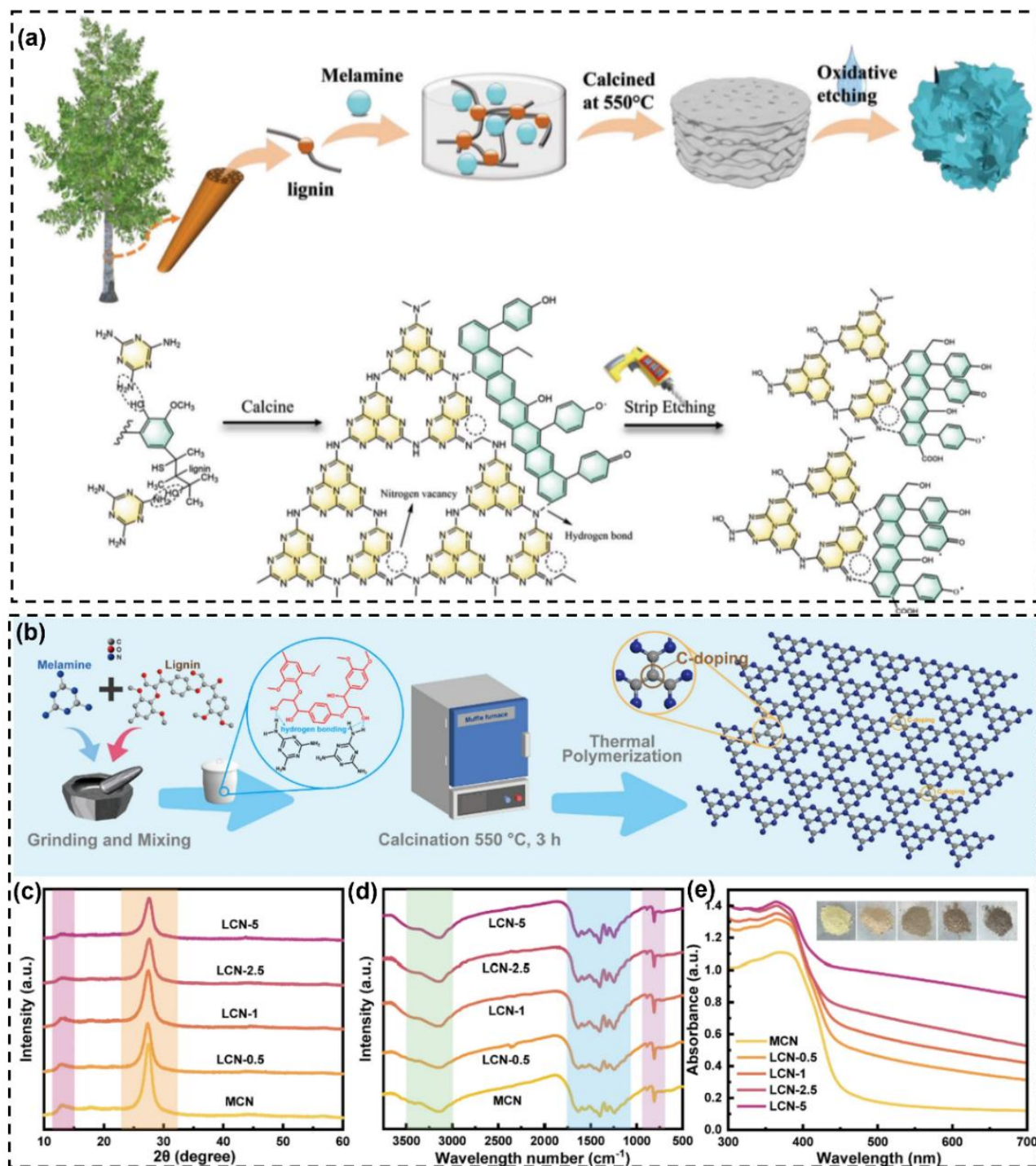


Fig. 9 (a) Schematics of the synthesis process of LCN-1 composites. Reproduced from ref.¹⁹ (b) Schematic for the preparation of the lignin C-doped g-C₃N₄. (c) The XRD, (d) the FT-IR, and (e) the UV-vis DRS images of MCN and LCN. Reproduced from ref.²⁰

severe charge recombination. Peng and co-workers^[66] integrated biomass-derived carbon rings with heptazine units via π -conjugation to construct a biochar-welded donor-acceptor (D-A) architecture in g-C₃N₄. Such a

built-in D-A configuration generates an intrinsic driving force that promotes electron delocalization and directional charge transport. Meanwhile, interlayer π - π stacking among carbon rings provides efficient out-of-

plane migration pathways for electrons across the layered structure. The resulting g-C₃N₄ with biochar-welded D-A structure enhanced the yield of xylonic acid from biomass monosaccharides to 87.52%. Mechanistic investigations confirmed the dominant role of superoxide radicals ($\cdot\text{O}_2^-$) and distinguished singlet oxygen ($^1\text{O}_2$) generation pathways, verifying that $^1\text{O}_2$ contributed via an energy-transfer process. This work establishes a general strategy for designing D-A structured g-C₃N₄-based photocatalysts toward efficient photocatalytic reforming of biomass.

3.4 Others

In addition to cellulose and lignin, a variety of other biomass resources can be employed for the functional modification of g-C₃N₄. For instance, chitosan, as a typical nitrogen-rich biomass, can not only act as an extra nitrogen source to participate in the polymerization process but also function as a soft template to induce in-situ nitrogen doping and facilitate the formation of porous structures during thermal polymerization, thus effectively regulating the electronic structure and surface morphology of g-C₃N₄.^[67] Moreover, algal biomass such as spirulina can serve as a sacrificial template that decomposes at high temperatures to construct interconnected porous frameworks for g-C₃N₄, which can significantly increase the specific surface area, expose more catalytic active sites, and optimize light absorption and charge carrier migration behaviors simultaneously.^[68] This strategy not only remarkably enhances the photocatalytic performance of g-C₃N₄, but also provides a facile and feasible pathway for the low-cost and large-scale preparation of high-performance g-C₃N₄-based photocatalytic materials, promoting the organic integration of biomass resource utilization and the green synthesis of high-efficiency

catalytic materials. For example, Yang and co-workers^[69] developed a green, facile biomass-derived strategy to fabricate hydroxylated carbon nitride nanosheets using urea and sucrose as bio-based precursors, followed by the construction of conjugated polyelectrolyte-modified CNOH heterojunctions for efficient photocatalytic hydrogen evolution. Two typical CPEs, cationic PFNBr and anionic PCP-2F-Li were selected to regulate the layer stacking and microstructure of CNOH. The CPEs were tightly coupled with bio-derived CNOH via strong interfacial hydrogen bonding and π - π stacking interactions, achieving well-matched energy level structures, optimized electronic state distribution, and excellent surface hydrophilicity, which significantly promoted the separation and migration efficiency of photogenerated charge carriers.

Different biomass sources should be rationally selected according to their intrinsic chemical features and target photocatalytic functions. As summarized in **Table 1**, cellulose and its derivatives are particularly suited for hydrogen-bond construction and proton-transfer regulation, lignin is advantageous for carbon doping and conjugated-domain modulation, chitosan serves as a nitrogen-rich platform for surface functionalization, algal biomass offers heteroatom-rich templating capability, and biochar functions as an efficient mediator for interfacial charge transfer.

Collectively, biomass engineering provides a green, cost-effective, and multifunctional approach to tailor the electronic structure, surface chemistry, and morphology of g-C₃N₄. These advances not only enhance photocatalytic performance across diverse applications including energy conversion and environmental remediation but also promote the valorization of abundant lignocellulosic biomass, bridging sustainable resource utilization and green catalytic chemistry.

Table 1. Comparative roles of different biomass in regulating g-C₃N₄ photocatalysts.

Biomass	Key feature	Main role in g-C ₃ N ₄ engineering	Advantage	Limitation	Refs.
Cellulose/cellulose derivatives	Rich in OH/COOH functional groups	Hydrogen bonding; proton relay	Hydrogen bond network, fast PCET	Weak thermal stability	[18,58,59]
Lignin	High carbon content.	Carbon doping; conjugated domains	Broad light absorption; electron delocalization	Complex structure; pyrolysis energy cost	[22,27,61,63]
Chitosan	Amino-rich polysaccharide	N doping; adsorption-assisted catalysis	Adds N sites; enriches pollutants	Solubility depends on acidic media	[67]
Algal biomass /spirulina	Mineral-rich biotemplate	Sacrificial template; dispersed active sites	Enables porous architectures	Thermal stability	[68]
Biochar / biomass carbon	Porous carbon	Electron mediator; heterojunction/defect regulator	Fast charge transport; photothermal effect	Often requires energy intensive carbonization	[69], [66, 70]

4. Enhancement strategies for biomass-engineered g-C₃N₄

The remarkable photocatalytic performance of biomass-engineered g-C₃N₄ is mainly derived from the multi-dimensional structural and electronic regulation effects introduced by biomass components. [2, 71] Biomass with abundant functional groups and diverse morphologies can interact with the precursor and framework of g-C₃N₄ during thermal polymerization, thus triggering multiple synergistic modification effects. In this section, we systematically elaborate the enhancement pathways of biomass engineering on the photocatalytic activity of g-C₃N₄. On the one hand, hydroxyl- and amino-rich biomass promotes interfacial interaction and charge separation through hydrogen bond engineering. [18, 26] On the other hand, biomass-derived carbon or heteroatom-doped components can construct tight heterojunctions, optimize band structure and accelerate carrier transfer. [69] Meanwhile, the decomposition of biomass templates can induce defect engineering, generating rich vacancy defects and porous structures. These strategies synergistically broaden the light absorption range, increase specific surface area and active sites, suppress charge recombination, and ultimately significantly boost the intrinsic photocatalytic activity of g-C₃N₄.

4.1 Hydrogen bonds engineering

Biomass featuring abundant hydroxyl and amino groups can form a stable, continuous hydrogen-bonding network with the heptazine and triazine repeating units of g-C₃N₄ during in-situ polymerization or solution-based composite fabrication. This hydrogen-bonding network, as a class of non-covalent intermolecular interaction, enables intimate, reduces interfacial defects interfacial contact between the biomass moieties and the g-C₃N₄ framework, and in turn establishes a continuous, low-resistance charge transfer channel across the composite interface. Through this well-defined interfacial charge transfer system, the hydrogen bonding interactions effectively suppress the recombination of photogenerated electron-hole pairs, precisely modulate the interfacial electron density distribution, and optimize the separation and migration dynamics of charge carriers, thereby directly enhancing the photocatalytic redox activity of the as-fabricated composite material. For example, our groups [18] demonstrated that hydroxyl-rich microcrystalline cellulose (MCC) can form strong intermolecular hydrogen bonds with g-C₃N₄, which significantly

promotes charge separation and suppresses recombination of photogenerated electron-hole pairs, thus greatly boosting photocatalytic tetracycline degradation and hydrogen evolution activity. (Fig. 10a-b) Furthermore, in-depth studies found that the construction of a hydrogen bonds network between carboxyl-functionalized cellulose nanofibrils (f-CNF) and CdS/g-C₃N₄ (CdS/PCN) S-scheme heterojunctions enhanced proton-donating capacity, effectively facilitated PCET process (Fig. 10c), lowered the reaction energy barrier of the *OOH intermediate, and ultimately achieved a photocatalytic activity of 2867 $\mu\text{mol} \cdot \text{L}^{-1} \cdot \text{h}^{-1}$. [26] (Fig. 10d)

4.2 Defect engineering

Defect engineering is an important approach to optimize the band structure of g-C₃N₄ and enhance the separation efficiency of photogenerated electron-hole pairs. Nonmetal doping can modify the g-C₃N₄ structure through framework atom substitution or surface grafting, while defect engineering can regulate the carbon nitride framework without introducing extrinsic metal elements; both strategies can disrupt the ordered heptazine ring structure of g-C₃N₄, induce planar polarization and charge redistribution. Through the rational selection of biomass precursors and precise control of synthetic processes, the controllable construction of elemental doping and vacancy defects can be simultaneously achieved, which finely tailors the microstructure and electronic properties of g-C₃N₄, thereby providing new insights and breakthrough directions for the development of photocatalytic technology. [72] For example, our groups [27] designed biochar-tailored g-C₃N₄ (PCCN-x) with controllable carbon doping and nitrogen vacancies (Fig. 11a), which activated CO₂ molecules and promoted C-C coupling to selectively generate C₂H₆. Furthermore, the fabricated PCCN-x with sp³-hybridized C bridges and tunable N defects, which constructed a strong dipole field to boost charge transport and lowered the energy barrier of *OOH intermediate, realizing a piezo-photocatalytic H₂O₂ production rate of 4.61 mmol g⁻¹ h⁻¹ even in pure water system (Fig. 11b-c). [70] Peng *et al.* [66] fabricated graphitic carbon nitride (GM-CN) integrated with biochar-welded donor-acceptor (D-A) architecture and defect engineering through the self-assembly and thermal copolymerization of melamine and glucosamine. (Fig. 11d) During the polycondensation process, the carbocyclic units derived from glucosamine were covalently incorporated into heptazine frameworks, which allowed the precise modulation of carbon doping concentration and

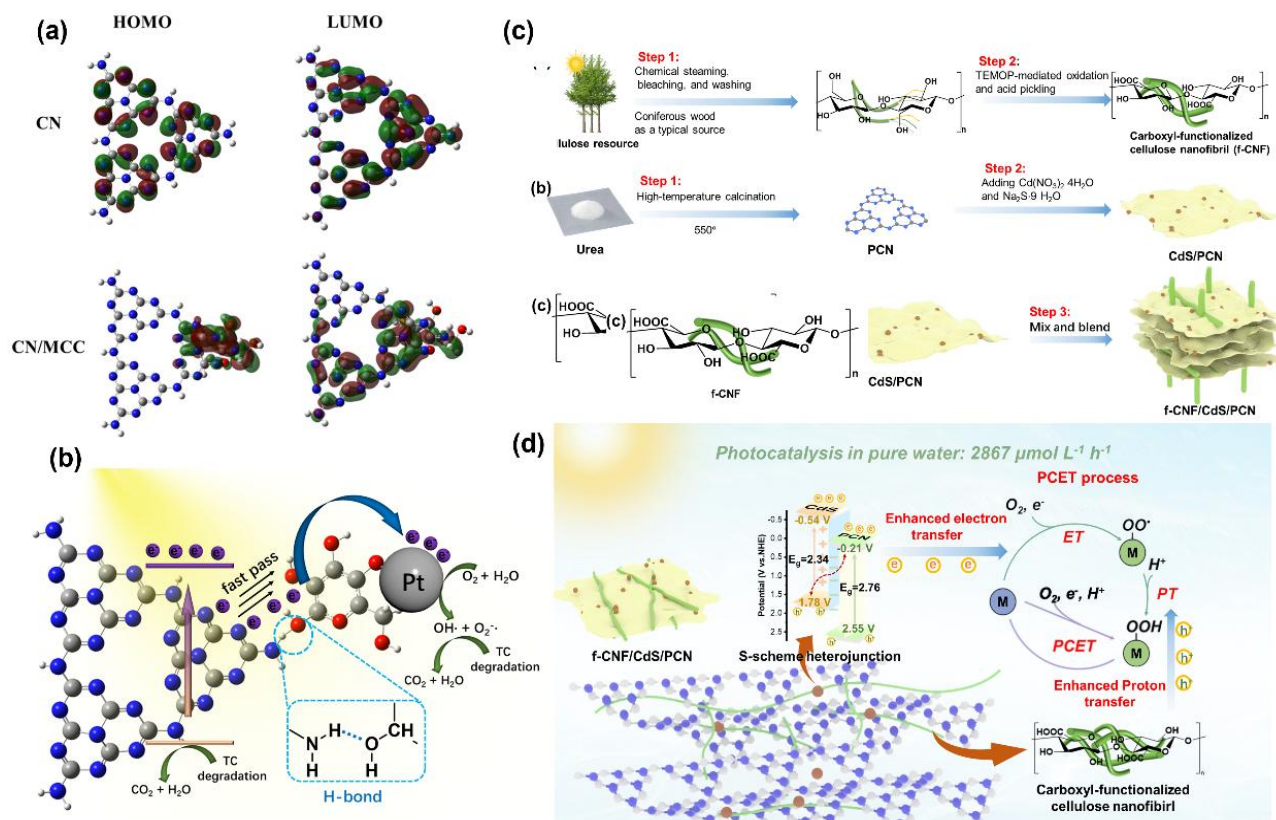


Fig. 10 (a) Molecular orbital distribution of the proposed CN and MCC/CN fragments. (b) A brief diagram of photocatalytic mechanism. Reproduced from ref.⁶ (c) Schematic illustration of synthesis routes for f-CNF, CdS/PCN, and f-CNF/CdS/PCN. Reproduced from ref.¹¹

structural defect density. Characterizations by electron paramagnetic resonance (EPR) and solid-state ^{13}C nuclear magnetic resonance (^{13}C NMR) demonstrated that defect-related signals were gradually intensified with elevated doping levels, indicating the promoted concentration of delocalized electrons and increased abundance of active defect sites. The introduction of carbon-ring units triggered a downshift of the band structure, which broke the symmetric charge distribution in pristine $\text{g-C}_3\text{N}_4$ and accelerated the directional electron transfer toward tri-s-triazine segments. Consequently, the electrons in the lowest unoccupied molecular orbital (LUMO) of GM-CN were concentrated in the conjugated defect regions between carbon rings and heptazine rings, while the holes in the highest occupied molecular orbital (HOMO) were localized around the defect-containing tri-s-triazine rings. Such defect-mediated spatial charge separation effectively optimized the electronic structure of $\text{g-C}_3\text{N}_4$, thereby substantially boosting its photocatalytic activity toward biomass conversion.

(Fig. 11e-f)

4.3 Heterojunction engineering

The construction of composite systems is a core strategy to modulate the electronic band structure of $\text{g-C}_3\text{N}_4$. These systems are categorized into homojunctions and heterojunctions including type I, type II, Z-scheme, and S-scheme configurations, with most existing studies focusing on $\text{g-C}_3\text{N}_4$ composites integrated with metal-based materials (Fig. 12a).^[3,73-75] In contrast to high-cost noble metal modification and conventional metal-based heterojunctions that carry inherent metal ion leaching risks, $\text{g-C}_3\text{N}_4$ heterojunctions built with sustainable, eco-friendly biomass offer pronounced advantages. These biomass-derived heterojunctions deliver high photocatalytic activity and excellent cycling durability without secondary environmental contamination, representing a key development direction for the green modification of $\text{g-C}_3\text{N}_4$.^[76,77] Biomass-derived carbon materials

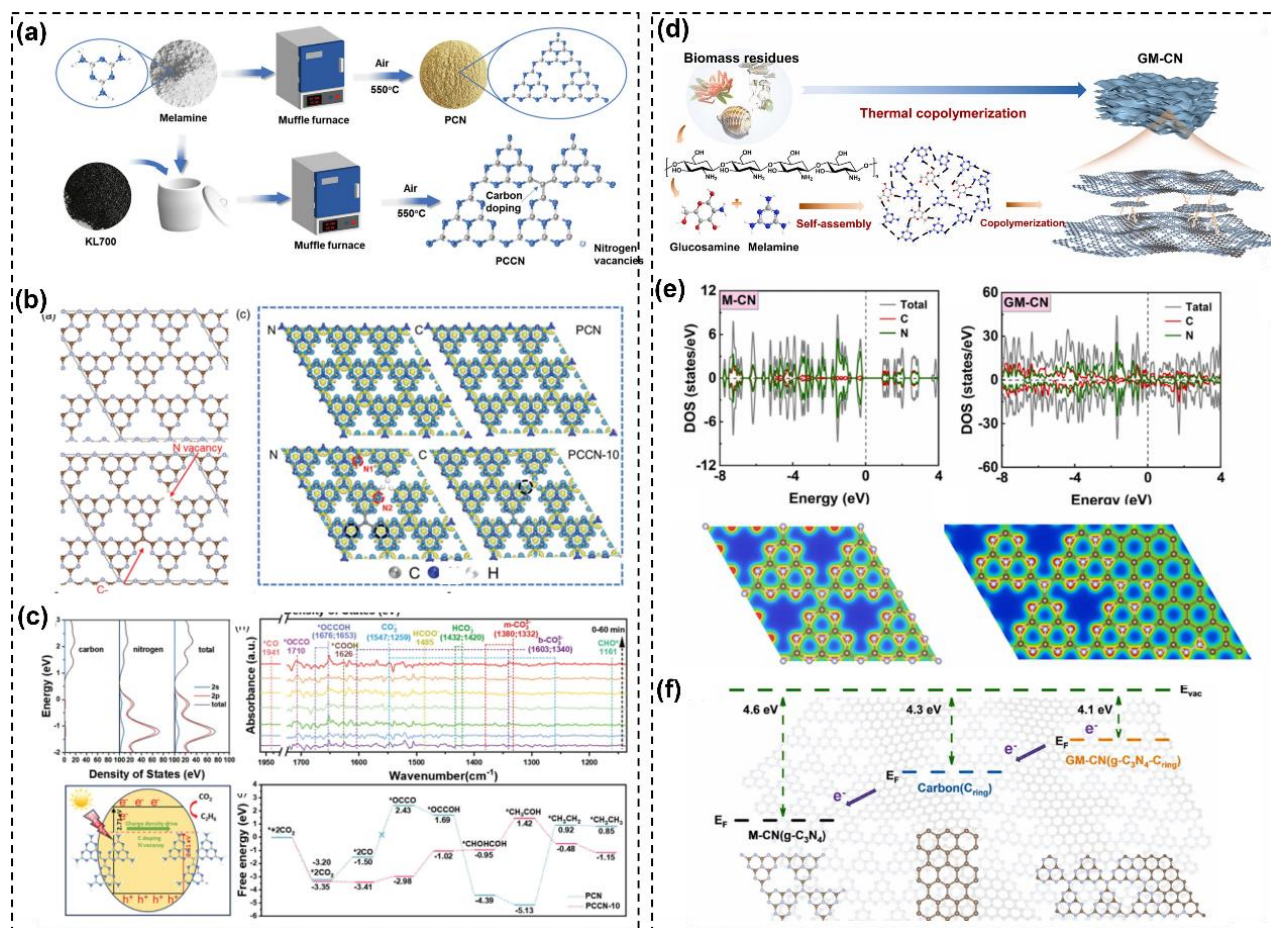


Fig. 11 (a) Schematic illustration of the synthesis route of PCCN. (b) The model structures and difference in electron density of elemental C and elemental N for PCN and PCCN-10. (c) In situ DRIFTS detections on the PCCN-10 photocatalyst in CO₂ atmosphere under irradiation, Proposed mechanism for the photocatalytic reactions in PCCN-10, and calculated free energy diagrams for CO₂ reduction. Reproduced from ref.^[12] (d) Scheme of the preparation of xGM-CN. (e) Calculated DOSs for M-CN and GMCN, and calculated DOSs for M-CN and GMCN. (f) Fermi energy level profile for M-CN, carbon and GM-CN. Reproduced from ref.^[22]

form a π - π conjugated heterojunction with g-C₃N₄, in which the carbon phase acts as an ultrafast electron bridge to directional export photogenerated electrons, reduce interfacial charge-transfer resistance, and activate O₂ for efficient H₂O₂ production. The optimized CN/CFs heterojunction delivers a H₂O₂ generation rate up to 1.31 mmol·L⁻¹·h⁻¹, far exceeding pure g-C₃N₄. Furthermore, Zhou *et al.*^[69] employed an aqueous urea-sucrose precursor to fabricate a type-II CPEs/CNOH heterojunction mediated by conjugated polyelectrolytes (CPEs). Hydrogen bonds and π - π stacking synergistically strengthen interfacial coupling, driving the exfoliation of hydroxylated g-C₃N₄ into a porous, wrinkled nanostructure (Fig. 12b). This extended visible-light absorption and accelerated spatial charge separation.

Collectively, these strategies broaden light

absorption, increase specific surface area and active sites, and suppress charge recombination, providing a systematic framework for the rational design of high-performance, green g-C₃N₄-based photocatalysts.

5. Applications of biomass-engineered g-C₃N₄ photocatalysts

The biomass-engineering strategy described above optimizes the physicochemical properties and electronic structure of g-C₃N₄, endowing this material with notable advantages in photoreduction applications. By tailoring the bandgap, enhancing interfacial charge separation and transfer, and improving substrate

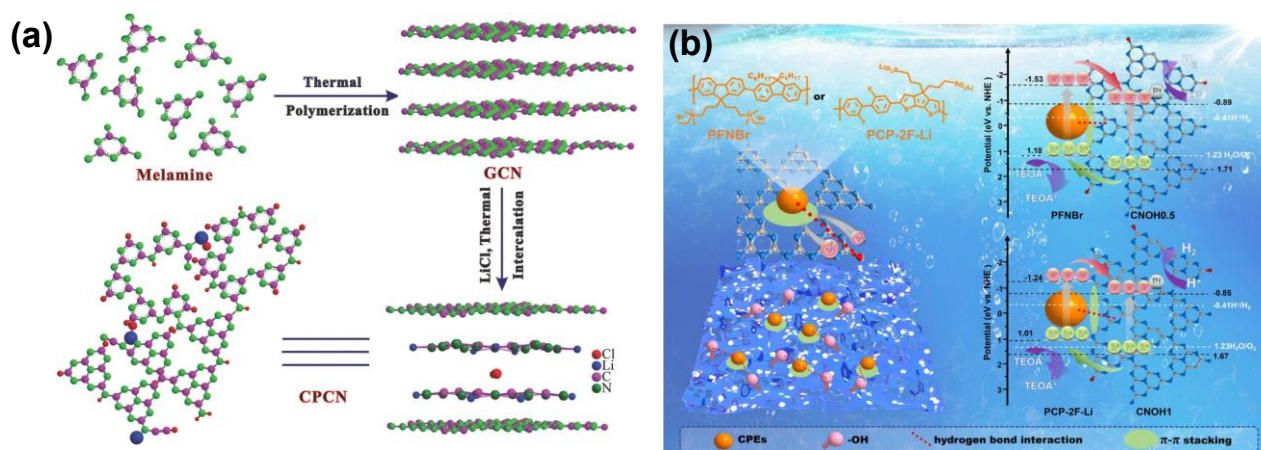


Fig. 12 (a) The proposed approach for the preparation of CPCN Reproduced from ref.⁷³ (b) The proposed photocatalytic hydrogen evolution (PHE) mechanism of conjugated polyelectrolytes (CPEs)/hydroxylated CN (CNOH) heterojunction. Reproduced from ref.^[69]

adsorption capacity, biomass-modified g-C₃N₄ photocatalysts achieve excellent catalytic activity and selectivity in typical photoreduction reactions, including water splitting for H₂ evolution, H₂O₂ production, CO₂ reduction, and organic pollutant degradation. Furthermore, the inherent green synthesis characteristics of this approach eliminate the risk of secondary pollution associated with conventional chemical modification methods, thereby conferring both high reduction efficiency and environmental compatibility upon the resulting material.

Collectively, biomass-derived engineering offers a sustainable and high-performance route for designing g-C₃N₄-based photoreduction catalysts. Representative research advances in this field are summarized in **Table 1**.

5.1 Photocatalytic water splitting

Photocatalytic water splitting converts solar energy into storable chemical fuels (e.g., H₂ or O₂), offering a sustainable route to address energy and environmental challenges.^[78-84] Since Wang and colleagues first used g-C₃N₄ for photocatalytic water splitting to produce H₂ and O₂ in 2009^[85] (**Fig. 13a**), the field has attracted considerable attention. g-C₃N₄ is a typical semiconductor with a bandgap of approximately 2.7 eV, a suitable band structure, and good stability for overall water splitting^[86, 87] (**Fig. 13b**). Under visible-light excitation, its conduction band potential (-1.3 V vs. NHE) is more negative than the reduction potential of H⁺/H₂ (-0.41 V vs. NHE), enabling water reduction to H₂^[88] (**Fig. 13c**). Meanwhile, its valence band potential (+1.4 V vs. NHE) is more positive than the

oxidation potential of O₂/H₂O (+1.23 V vs. NHE), allowing water oxidation to O₂. Consequently, g-C₃N₄ shows significant potential for photocatalytic water splitting applications.

By utilizing biomass-derived carbon to modulate the electronic structure, facilitate charge transfer, and introduce photothermal effects, the carrier recombination in g-C₃N₄ is effectively suppressed, thereby significantly enhancing its photocatalytic hydrogen evolution performance. Ullah *et al.*^[89] developed a facile one-step annealing route to synthesize carbon-doped g-C₃N₄ (CCN-X) using urea and L-aspartic acid as precursors (**Fig. 13d**). Carbon doping extended visible-light absorption, narrowed the band gap, and promoted the separation and transfer of photogenerated charge carriers, leading to drastically enhanced photocatalytic H₂ evolution. Under visible-light irradiation ($\lambda \geq 420$ nm), the optimized CCN-8 catalyst delivered a maximum H₂ production rate of 2192.2 $\mu\text{mol}\cdot\text{h}^{-1}\cdot\text{g}^{-1}$, 6.6-times higher than pristine g-C₃N₄ (333.0 $\mu\text{mol}\cdot\text{h}^{-1}\cdot\text{g}^{-1}$). CCN-8 also exhibited an apparent quantum efficiency of 6.57% at 420 nm and excellent stability over 16 h of cycling. Gao *et al.*^[90] prepared a biomass-derived carbon/porous carbon nitride composite (BC/PCN) using an in-situ compositing method (**Fig. 13e**). Through close interfacial bonding, the composite modulated the electronic structure and promoted directional migration of photogenerated carriers. Owing to its ultralow light reflectivity, biomass-derived BC enabled near-full-spectrum light harvesting, causing a redshift in the composite's absorption edge and narrowing its bandgap. Meanwhile, BC acted as an efficient charge-transfer bridge, rapidly conveying photogenerated

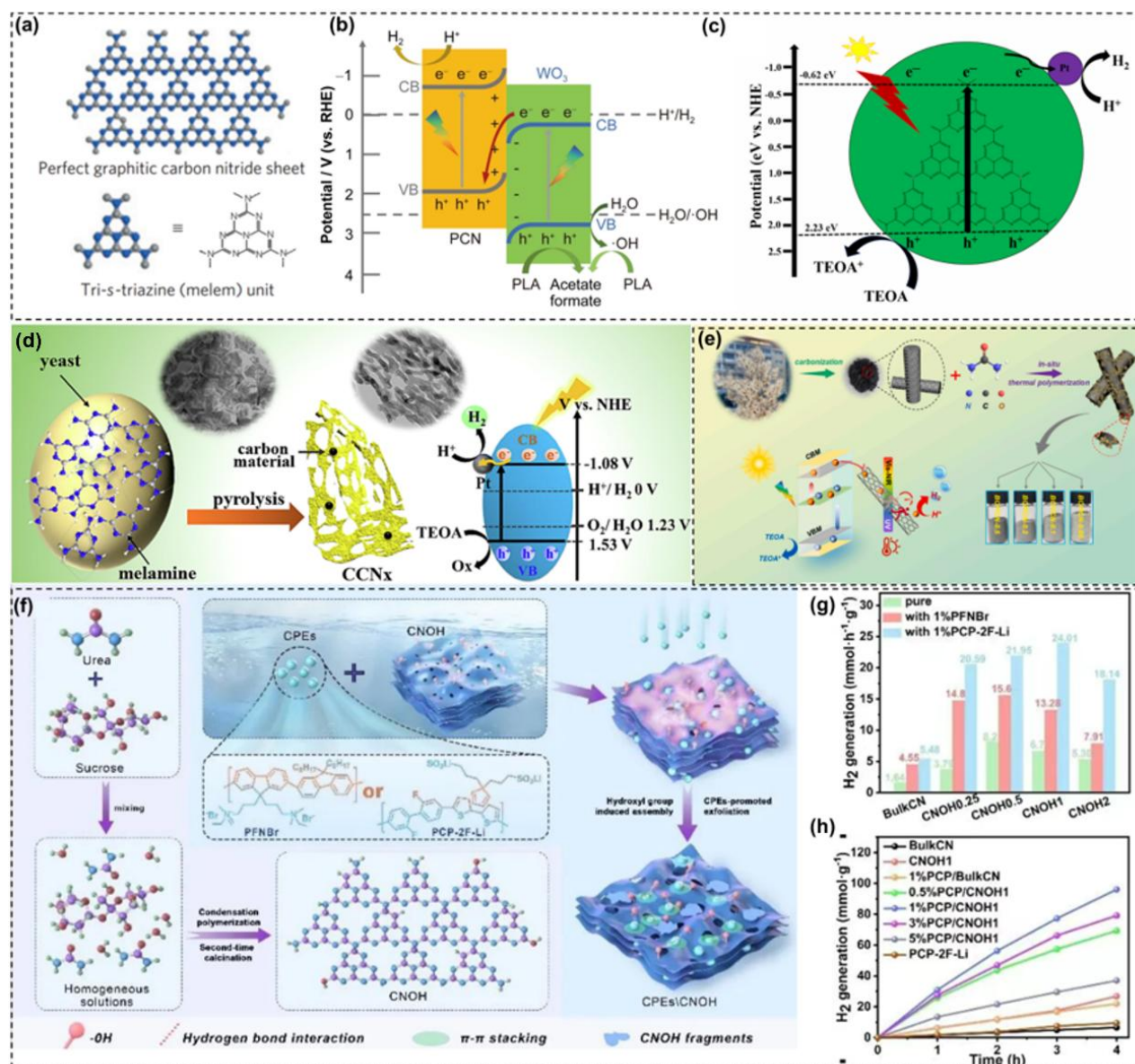


Fig. 13 (a) Crystal structure of graphitic carbon nitride sheet and its basic tri-s-triazine (melem) repeating unit. Reproduced from ref.^[85] (b) Band structure alignment and photocatalytic mechanism of PCN/WO₃ heterojunction for simultaneous H₂ evolution. Reproduced from ref.^[36] (c) Schematic illustration of energy band structure photocatalytic H₂ production over Pt/g-C₃N₄ composite. Reproduced from ref.^[88] (d) Synthetic process of yeast-templated porous carbon-doped g-C₃N₄ (CCN_x) and its photocatalytic H₂ evolution mechanism. Reproduced from ref.^[89] (e) Fabrication route of biomass-derived carbon/g-C₃N₄ heterojunction and its photocatalytic pollutant degradation mechanism. Reproduced from ref.^[90] (f) Schematic representation of the synthesis of hydroxylated g-C₃N₄ and conjugated polyelectrolyte (CPE)-modified CNOH heterojunctions via hydrogen-bonding induced assembly and exfoliation. (g) Photocatalytic H₂ evolution rates of bulk CN, CNOH and CPE-modified CNOH samples with different CPE loadings. (h) Time-dependent photocatalytic H₂ production curves of bulk CN, CNOH and various CPE-modified g-C₃N₄ composites under visible light irradiation. Reproduced from ref.^[69]

electrons from PCN to active sites and thereby greatly suppressing carrier recombination. The photothermal effect of BC also significantly enhanced the reaction kinetics of the photocatalytic system. The optimal

BC/PCN-0.1 composite achieved a HER rate of 4.98 mmol·g⁻¹·h⁻¹ under simulated solar irradiation, representing a 2.1 times improvement over pristine PCN (2.35 mmol·g⁻¹·h⁻¹). An apparent quantum

efficiency of 4.82% at 420 nm confirmed the crucial role of efficient charge separation at the BC/PCN interface in boosting catalytic performance. After five cycles, the HER activity remained 78% of its initial value. Yang *et al.* [69] fabricated type-II heterojunctions of conjugated polyelectrolyte (CPE)-assisted hydroxylated g-C₃N₄ (CNOH) (**Fig. 13f**). The optimal 3% PFN/CNOH_{0.5} and 1% PCP/CNOH (1.5 wt% Pt) delivered photocatalytic H₂ evolution (PHE) rates of 22.75 and 24.01 mmol g⁻¹ h⁻¹ under visible light (600 mW cm⁻²), 13.87- and 14.64 times higher than bulk g-C₃N₄, respectively (**Fig. 13g-h**). The remarkable PHE enhancement arises from well-matched energy alignment between CPEs and CNOH, enlarged surface area via CPE-facilitated exfoliation, extended visible-light absorption from sucrose and CPE doping, strengthened interfacial interactions through hydrogen bonding and π - π stacking, and improved hydrophilicity endowed by sucrose modification.

5.2 Photocatalytic H₂O₂ production

Hydrogen peroxide (H₂O₂), a green oxidant and bleaching agent, finds extensive applications in water treatment, food processing, medical disinfection, and chemical synthesis. [91-93] Photocatalytic H₂O₂ synthesis proceeds under mild conditions, combining energy efficiency with environmental benignity, and has thus become a research focus. The conduction band of g-C₃N₄ lies at approximately -1.3 eV, providing an ideal thermodynamic potential for O₂ reduction (-0.33 V vs. NHE); its valence band at about +1.4 eV is considerably lower than that of most metal oxides, facilitating the suppression of H₂O₂ decomposition. [94-96]

Optimizing the light absorption range and band structure of g-C₃N₄ through biomass regulation enhances solar energy utilization, which benefits photocatalytic H₂O₂ synthesis. Chen *et al.* [70] developed biochar-tailored carbon nitride nanosheets (PCCN-x) featuring carbon bridges and nitrogen defects for high-efficiency piezo-photocatalytic H₂O₂ production. The introduction of sp³-hybridized carbon bridges distorted the planar structure of g-C₃N₄ and strengthened π - π delocalization, whereas nitrogen defects broke the structural symmetry to generate a pronounced dipole field, driving spontaneous polarization and oriented charge migration. (**Fig. 14a-c**) The optimal PCCN-10 achieved a remarkable H₂O₂ yield of 4.61 mmol g⁻¹ h⁻¹ without cocatalysts under light-ultrasound co-irradiation, and maintained a production rate of 2.19 mmol g⁻¹ h⁻¹ in pure water with stable activity over five cycles. Experimental and theoretical analyses confirmed that the dipole field

significantly boosted piezoelectric polarization and charge separation, lowered the energy barrier for *OOH formation, and enabled efficient H₂O₂ generation via an indirect two-electron O₂ reduction pathway (**Fig. 14d**). This work provides a defect-engineering design principle for piezo-photocatalytic materials toward sustainable H₂O₂ production.

5.3 Photocatalytic CO₂ reduction

Photocatalytic conversion of CO₂ into value-added hydrocarbons provides an effective strategy to alleviate energy shortages. [97-101] On g-C₃N₄ surfaces, bridging and edge N atoms serve as primary active sites, where lone-pair electrons coordinate with the C atom of CO₂ molecules, promoting efficient CO₂ adsorption in aqueous environments. Moreover, g-C₃N₄ has a relatively negative conduction band potential (approximately -1.3 V vs. NHE), significantly lower than the standard reduction potentials for converting CO₂ into various carbon products (e.g., CO₂/CO: -0.53, CO₂/CH₄: -0.24, CO₂/CH₃OH: -0.38, CO₂/HCOOH: -0.61 V vs. NHE), indicating sufficient thermodynamic reduction capability (**Fig. 15a-b**). [100,102]

Structural optimization and surface functionalization of g-C₃N₄ through biomass incorporation can mitigate its inherent limitations by enhancing visible light harvesting, CO₂ adsorption, and product desorption, thereby boosting CO₂ photoreduction capability. [103-106] From an application perspective, C₂H₆ is more valuable than C1 products because it is an energy-rich C2 hydrocarbon and an important feedstock for ethylene production. More importantly, C₂H₆ formation from CO₂ requires multi-electron/proton transfer coupled with C-C bond construction. Therefore, selective CO₂-to-C₂H₆ conversion over biomass-engineered g-C₃N₄ should be understood not only as activity improvement but also as selective manipulation of adsorption geometry, local electron density and reaction intermediates.

C-C coupling on carbon-doped/nitrogen-vacancy g-C₃N₄ is generally initiated by CO₂ adsorption and activation at electron-rich N-defective or C-bridged sites. The first proton-electron transfer generates *COOH, followed by dehydration/electron transfer to form *CO. When adjacent *CO or *CHO species are stabilized on neighboring active sites, their surface residence time increases and C-C coupling can proceed through *CO-*CO, *CO-*CHO or *CHO-*CHO coupling pathways, producing key *OCCO, *COCHO or related C₂ intermediates. Subsequent stepwise hydrogenation and deoxygenation can convert these C₂ intermediates into *CH₃CH₃ and finally release

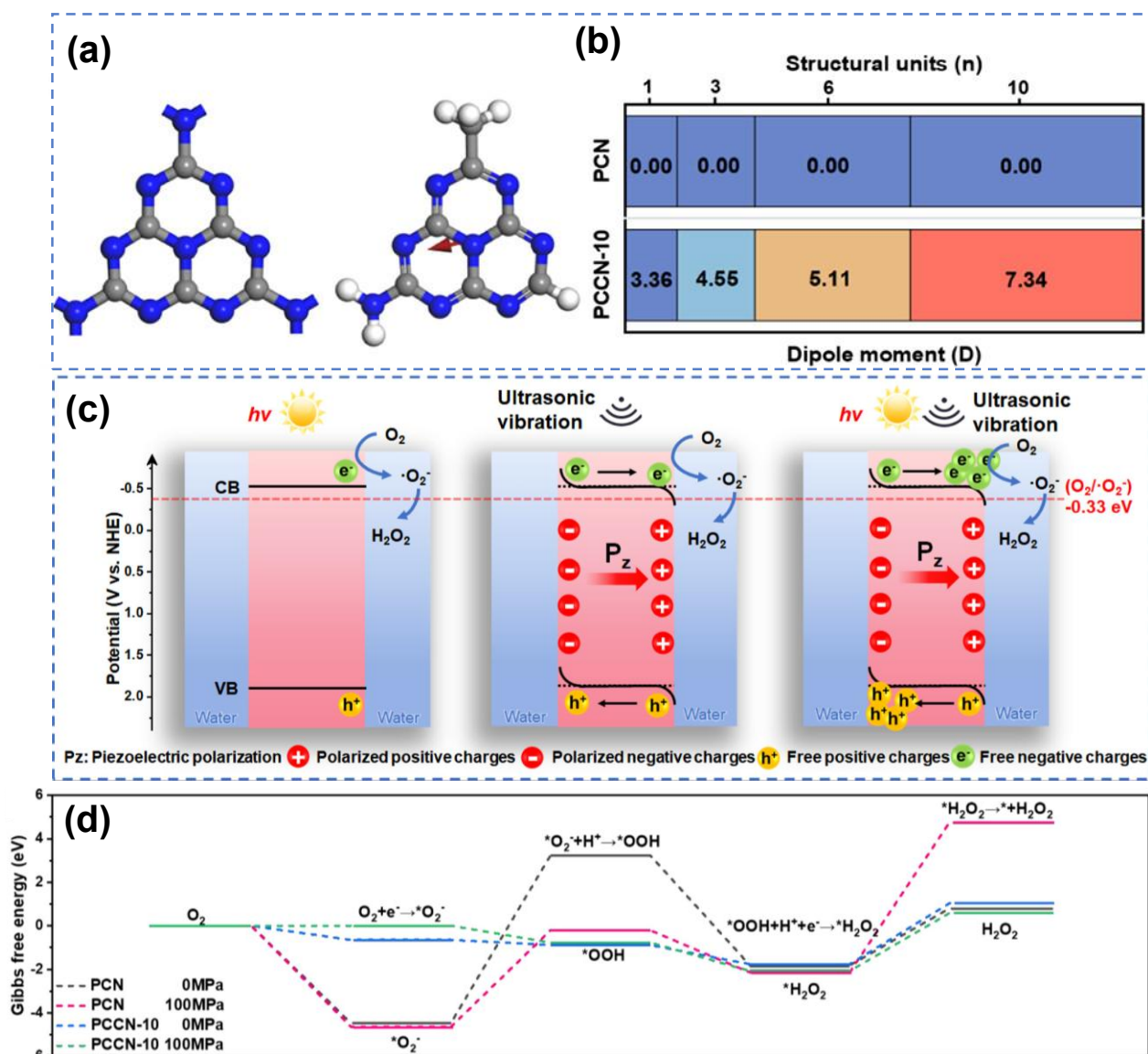


Fig. 14 (a) Structural unit and dipole moments of PCN and PCCN-10. (b) Dipole moments of PCN and PCCN-10 with different structural unit numbers. (c) Proposed charge transfer and reaction mechanism under light and ultrasonic vibration. (d) Gibbs free energy (ΔG) analysis of two-electron ORR in PCN and PCCN-10 systems. Reproduced from ref.^[70]

C_2H_6 .^[102] Our groups^[27] fabricated carbon-doped, nitrogen-vacancy-engineered g- C_3N_4 nanosheets (PCCN-x) using a lignin-biomass-derived precision molecular design strategy (**Fig. 15d**). The introduction of bridged C sites and N vacancies modulated the electronic structure and local electron density distribution, narrowing the bandgap and red-shifting the light absorption edge while promoting charge separation and suppressing photogenerated carrier recombination. This configuration enhanced CO_2 adsorption and activation significantly lowered the energy barrier for C-C coupling to form the key

*OCCO intermediate, and enabled highly selective photoreduction of CO_2 to C_2H_6 in pure water. The optimal PCCN-10 photocatalyst achieved a C_2H_6 production rate of $99.14 \mu mol \cdot g^{-1} \cdot h^{-1}$ with 80.33% selectivity, along with CO and CH_4 yields of 9.20 and $15.07 \mu mol \cdot g^{-1} \cdot h^{-1}$, respectively (**Fig. 15c, e-f**). This work achieved precision molecular engineering of g- C_3N_4 via biomass mediation, establishing a paradigm for rational photocatalyst optimization that aligns with green chemistry principles and sustainable development, and demonstrating significant potential for practical implementation.

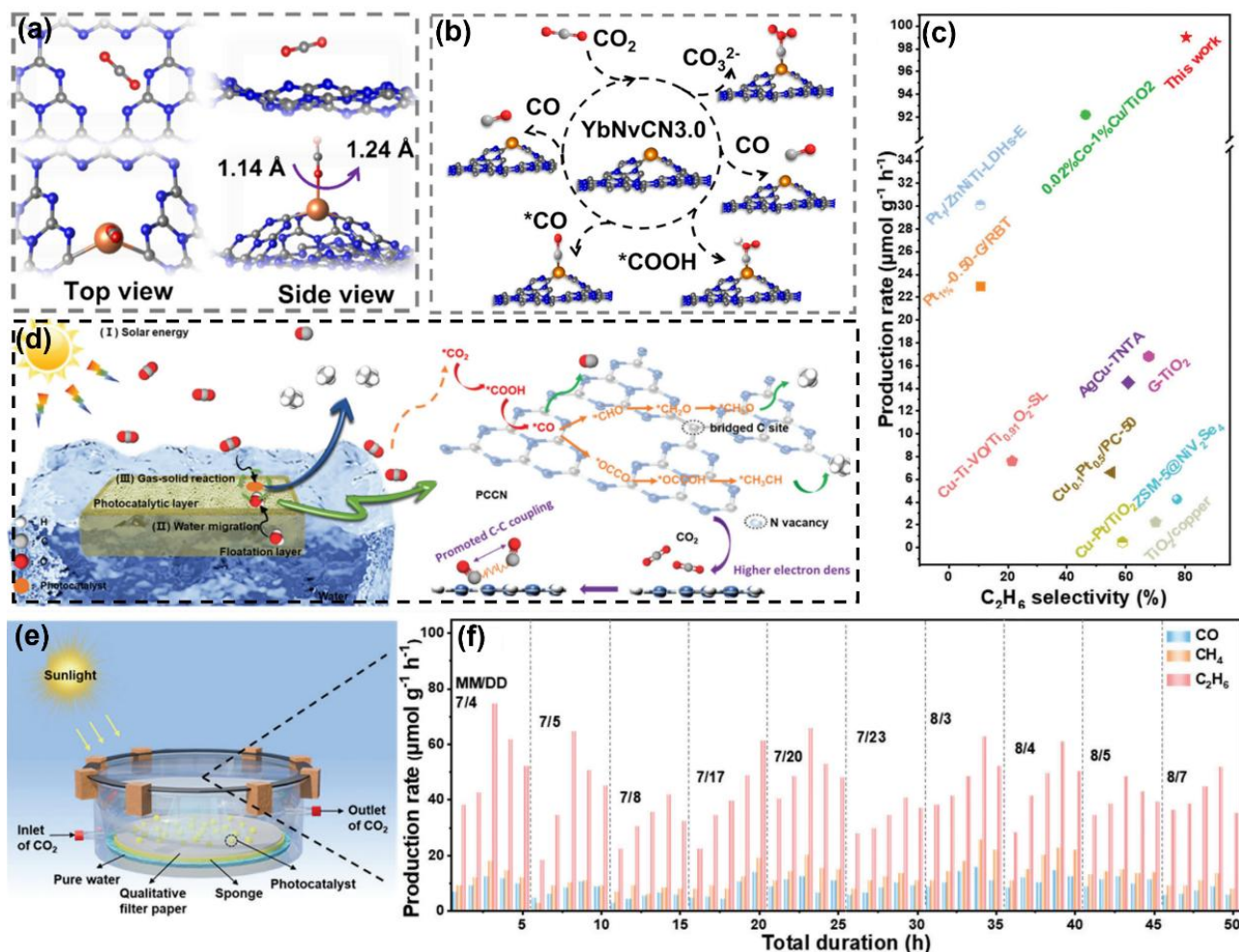


Fig. 15 (a) Top and side views of the optimized CO₂ adsorption configuration on nitrogen-vacancy-rich graphitic carbon nitride, with key bond lengths labeled. (b) Proposed reaction mechanism and elementary steps for photocatalytic CO₂ reduction to CO over the catalyst. Reproduced from ref.^[49] (c) Comparison of photocatalytic activity and selectivity for C₂H₆ production with other works. (d) Diagram illustration of photocatalytic CO₂ reduction over PCCN photocatalysts. (e) Diagram illustration for outdoor reaction pond in this photocatalytic system. (f) CO, CH₄, and C₂H₆ production rates of PCCN-10 in pure water under actual sunlight during the selected period of 11:00-16:00 for 50 h. Reproduced from ref.^[27]

5.4 Photocatalytic degradation of organic pollutants

As a green and sustainable technology, photocatalytic pollutant degradation holds great promise for environmental remediation.^[107-109] Sustainable biomass-derived strategies for engineering g-C₃N₄ have also shown remarkable performance in this context.^[110,111] The core mechanism involves the generation of reactive oxygen species (ROS, e.g., OH, O₂^{•-}, ¹O₂, and H₂O₂) driven by photogenerated carriers, followed by redox reactions. g-C₃N₄ exhibits both photocatalytic activity and notable adsorption capability. Its conduction band potential is sufficiently

more negative than the reduction potential of dissolved O₂ to superoxide radicals ($\cdot\text{O}_2^-$) ($\text{O}_2 + e^- \rightarrow \cdot\text{O}_2^-$, -0.33 V vs. NHE).^[112] Surface holes can oxidize H₂O to $\cdot\text{OH}$ or directly oxidize functional groups of organic pollutants. Additionally, singlet oxygen (¹O₂) can be generated via energy transfer or disproportionation of $\cdot\text{O}_2^-$.

However, similar to water splitting and CO₂ reduction, g-C₃N₄ exhibits limited active sites and rapid carrier recombination. Biomass-derived strategies can overcome these drawbacks by enhancing charge separation and ROS generation, embodying green principles from synthesis to application. Han *et al.*^[113] fabricated a wood pulp cellulose biochar/g-C₃N₄

(WPBC/g-C₃N₄) composite via hybridization, which efficiently activated peroxymonosulfate (PMS) to degrade diclofenac (DCF) under visible light (Fig. 16a). The optimal WPBC₅₀/g-C₃N₄ showed outstanding stability, retaining high DCF degradation efficiency after five cycles. Incorporation of WPBC narrowed the bandgap, enhanced visible-light absorption, and improved charge separation and PMS activation performance of g-C₃N₄. Both radical species ($\cdot\text{OH}$, h^+ , $\cdot\text{O}_2^-$) and nonradical pathways ($^1\text{O}_2$, electron

transfer) contributed to DCF degradation, with $^1\text{O}_2$ as the dominant reactive oxygen species. The C=O and N-(C)₃ groups served as active sites for PMS activation, and principal component analysis identified DCF concentration as the most influential factor (Fig. 16b-e). Tailored biomass sources can markedly enhance photocatalytic degradation efficiency. Such experiments provide new insights and prospects for the value-added utilization of biomass-modified g-C₃N₄ as a photocatalyst for degrading environmental pollutants.

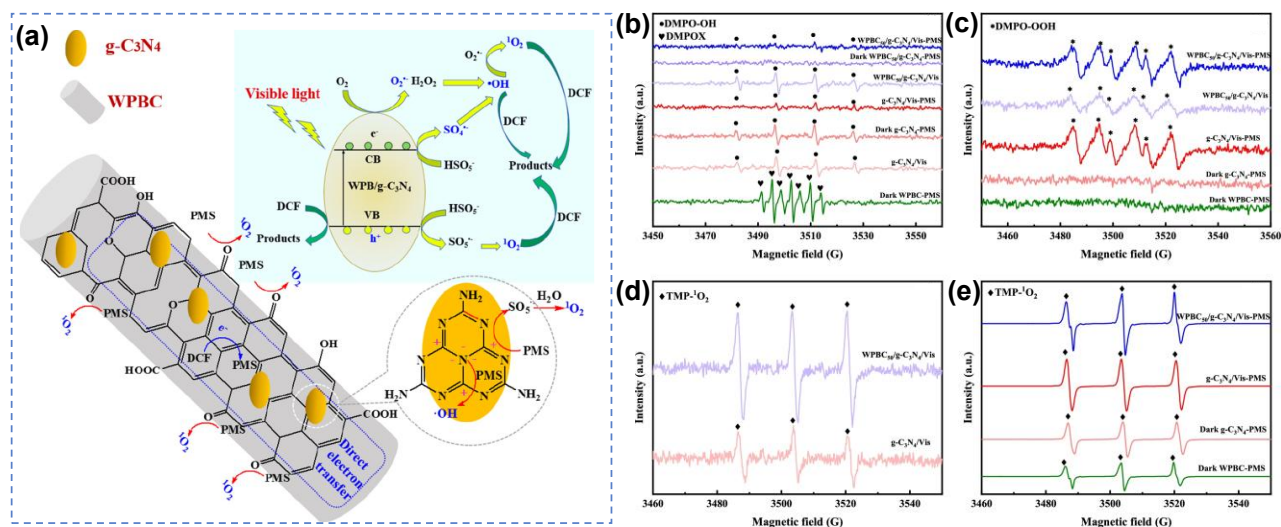


Fig. 16 (a) Wood pulp cellulose biochar (WPBC) improved the catalytic performance of g-C₃N₄ via both radical and nonradical mechanisms. (b) DMPO-OH and DMPOX spectra using 80 mM DMPO for 10 min reaction, (c) DMPO-OOH spectra using 80 mM DMPO for 10 min reaction, (d, e) TMP- $^1\text{O}_2$ spectra using 5.0 mM TMP for 10 min reaction (condition: $[\text{DCF}]_0 = 0.01$ mM, $[\text{catalyst}]_0 = 0.5$ g/L, $[\text{PMS}]_0 = 2.0$ mM). Reproduced from ref. [113]

5.5 Photocatalytic nitrogen (N₂) fixation

In addition, another photocatalytic application is nitrogen (N₂) fixation. Photocatalytic N₂ fixation is a key technology for energy and environmental remediation. [114, 115] It utilizes solar energy to fix nitrogen under ambient conditions, offering a low-carbon route for ammonia synthesis. [91, 114, 116–118] The mechanism involves photogenerated electrons (e⁻) reducing N₂ to NH₃ under catalytic action, while photogenerated holes (h⁺) are consumed via oxidation by sacrificial agents or H₂O. [114]

Biomass materials, particularly biomass carbon, possess a porous structure that confers exceptional adsorption advantages. Tang *et al.* [71] fabricated diphasic carbon-decorated carbon nitride (DC-CN) photocatalysts via a one-pot co-pyrolysis strategy using lotus root starch as a biomass precursor, simultaneously introducing in-plane fused carbon rings and physically piled carbon particles into the g-C₃N₄ framework. The

diphasic carbon synergistically created dual electron transfer pathways, optimized band alignment, broadened visible-light absorption, and greatly enhanced the separation efficiency of photogenerated carriers. Both carbon species acted as active sites to regulate electron transfer and lower the energy barrier for N₂ activation and hydrogenation. The optimal DC-CN0.1 achieved a superior NH₃ production rate of 167.35 $\mu\text{mol}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$ under visible light, five times higher than that of pure g-C₃N₄, with excellent cycling stability (Fig. 17a-b). Experimental characterizations and DFT calculations confirmed that the diphasic carbon synergy was responsible for the enhanced photocatalytic N₂ fixation, thereby enriching the metal-free skeleton engineering toolbox for photocatalysts (Fig. 17c-d).

Collectively, biomass-engineered g-C₃N₄ has demonstrated versatile and exceptional performance across diverse photocatalytic applications (Table 2). For H₂ evolution, the synergistic integration of C

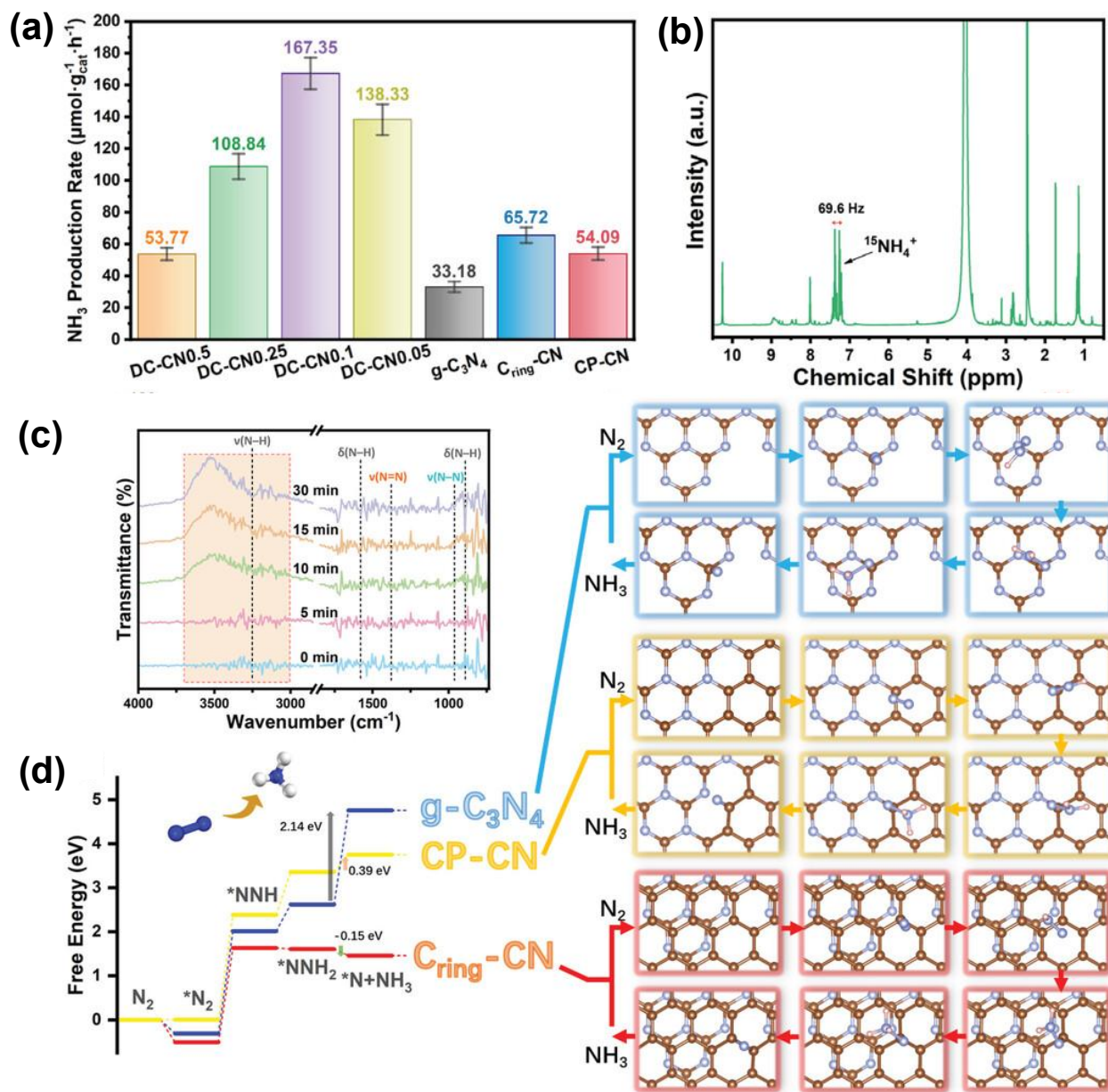


Fig. 17 (a) Production rates of NH₃ detected by Nessler's reagent in photocatalytic N₂ fixation tests with different catalysts. (b) ¹H NMR spectrum of the reaction solution from the isotopic labeling experiment on DC-CN0.1. (c) In situ DRIFT spectra during the photocatalytic N₂ fixation on DC-CN0.1. (d) Gibbs free energy diagrams for N₂ reduction on g-C₃N₄, C_{ring}-CN, and CP-CN, respectively. The corresponding optimized structures of various intermediates. Reproduced from ref. [71]

doping, heterostructure construction, and photothermal effects has enabled up to a 14.6 times enhancement in H₂ production rate relative to g-C₃N₄. For H₂O₂ synthesis, cooperative modulation of C bridges and N vacancies delivers a remarkable yield of 4.61 mmol·g⁻¹·h⁻¹ in the absence of any cocatalysts. In CO₂ photoreduction, a landmark breakthrough has been achieved in the highly selective conversion of CO₂ to C₂H₆ in pure water, opening a transformative avenue

for photocatalytic multi-carbon product synthesis. For organic pollutant degradation and nitrogen fixation, the porous architecture and interfacial regulation conferred by biomass-derived carbon have also substantially improved both reaction kinetics and long-term catalyst stability. These advances underscore the enormous untapped potential of biomass resources for the rational design of high-performance photocatalytic materials.

Table 2. Performance comparison of various biomass-engineered g-C₃N₄ photocatalysts.

Samples	Biomass raw materials	Irradiation condition	Strategy	Condition	Yield	Applications	Refs.
BC/PCN-0.1	Phragmites spikelets	300W xenon, AM 1.5G	Heterojunction engineering	100 mg catalyst, 55 mL TEOA, 220 mL +3wt.% Pt	4.98 mmol g ⁻¹ h ⁻¹	H ₂ production	[90]
CCN15	Yeast	300W xenon lamp, λ>420 nm	Defect engineering	50 mg catalyst, 10 vol% TEOA, 100 mL +3wt.% Pt	2704 μmol g ⁻¹ h ⁻¹	H ₂ production	[119]
CN-U ₃₀	Uracil	300W xenon lamp, λ>400 nm	Defect engineering	50 mg catalyst, 10 vol% TEOA, 100 mL +1wt.% Pt	5100.5 μmol g ⁻¹ h ⁻¹	H ₂ production	[120]
CNP-L _{5,0}	Lignin	300 W Xe lamp, λ>420 nm	Defect engineering	100 mg catalyst, 10% TEOA, 100 mL +3wt.% Pt	822.7 μmol g ⁻¹ h ⁻¹	H ₂ production	[121]
CCN-8	L-aspartic	300W xenon lamp, λ≥420 nm	Defect engineering	50 mg catalyst, 10 vol% TEOA, 100 mL +1wt.% Pt	2192.2 μmol g ⁻¹ h ⁻¹	H ₂ production	[89]
PCCN-10	Lignin-derived carbon	300W xenon lamp	Defect engineering	1 mg catalyst, 1.0 mL EtOH	C ₂ H ₆ : 99.14 μmol g ⁻¹ h ⁻¹ CO: 9.20 μmol g ⁻¹ h ⁻¹	CO ₂ reduction	[27]
50CQDs/CN	Licorice	300W xenon lamp, λ>420 nm	Heterojunction engineering	10 mg catalyst, 0.5 mL EtOH	CO: 28.9 μmol g ⁻¹	CO ₂ reduction	[122]
g-SB-HT-W	Sugarcane bagasse	14W LED light bulb	Heterojunction engineering	0.1 g catalyst, 1.0 mL EtOH	CO: > 600 nmol g ⁻¹	CO ₂ reduction	[106]
Fe-SA/g-C ₃ N ₄	Spirulina	300W xenon lamp	Defect engineering	10 mg catalyst, 2 mL EtOH, 1 mL H ₂ O, 9 mL CH ₃ CN	C ₂ H ₆ : 1.8 μmol g ⁻¹ h ⁻¹ CO: 16 μmol g ⁻¹ h ⁻¹	CO ₂ reduction	[68]
CN-HS	Phase-transitioned lysozyme	300W xenon lamp	Heterojunction engineering	30 mg catalyst, 1.0 mL TEOA, 1 mL water, 3.0 mL CH ₃ CN + 2,2-bipyridine and CoCl ₂ 6H ₂ O	CO: 1346 μmol g ⁻¹	CO ₂ reduction	[123]
CN-B/CS	Chitosan	Xenon lamp	Heterojunction engineering	-, 100 mg L ⁻¹ TC solution	Degradation 82.5%/4 h	Pollutant degradation	[124]
BC/g-C ₃ N ₄ /PDA	Bacterial cellulose	100-wat LED	Heterojunction engineering	20 mg catalyst, 10 mg L ⁻¹ methylene blue	Degradation 95.39%/150 min	Pollutant degradation	[125]
g-C ₃ N ₄ -U	Alginate floating beads	Solar lamp	Hydrogen bonds engineering	-, 100 mL, 0.5 g L ⁻¹ RhB solution	Degradation 90%/3 h	Pollutant degradation	[126]
CNG-JE	Lignocellulose-based juncus effusus	UV light	Heterojunction engineering	-, 20 mL, 50 g L ⁻¹ Reactive red 120	Degradation 99.80%/120 min	Pollutant degradation	[127]
CNG-JE	Lignocellulose-based juncus effusus	UV light	Heterojunction engineering	-, 20 mL, 50 g L ⁻¹ Acid yellow 11	Degradation 99.40%/120 min	Pollutant degradation	[127]
CNG-JE	Lignocellulose-based juncus effusus	UV light	Heterojunction engineering	-, 20 mL, 50 g L ⁻¹ Methylene blue	Degradation 99.40%/140 min	Pollutant degradation	[127]
HTCC	Cellulose	300W xenon lamp, λ>420 nm \		10 mg catalyst, 50 mL water + O ₂	1160 μmol g ⁻¹ h ⁻¹	H ₂ O ₂ production	[128]
HJ-C ₃ N ₄	Sodium citrate	300W xenon lamp, λ≥420 nm	Heterojunction engineering	0.02 g catalyst, 20 mL water + O ₂	115 μmol g ⁻¹ h ⁻¹	H ₂ O ₂ production	[129]
P-HTCC	Cellulose	PLS, λ≥420 nm \		10 mg catalyst, 50 mL water	920 μmol g ⁻¹ h ⁻¹	H ₂ O ₂ production	[130]
CN/CMCL	Cellulose	300W xenon lamp, λ≥420 nm	Hydrogen bonds engineering	25 mg catalyst, 25 mL water + O ₂	35.7 μmol g ⁻¹ h ⁻¹	H ₂ O ₂ production	[23]
CN@PDA-10	Polydopamine	300W xenon lamp, λ>400 nm	Hydrogen bonds engineering	10 mg catalyst, 50 mL water + O ₂	578.7 μmol g ⁻¹ h ⁻¹	H ₂ O ₂ production	[131]
PCCN-10	Lignin	300W xenon lamp, λ>420 nm	Defect engineering	50 mg catalyst, 20 mL, 10%Vol EtOH + O ₂	4.61 mmol g ⁻¹ h ⁻¹	H ₂ O ₂ production	[70]
BiOI/BC/CN	Rice husk-derived biochar	50W lamp, λ≥420 nm	Heterojunction engineering	20 mg catalyst, 50 mL, 10% IPA + O ₂	2.61 mmol·g ⁻¹	H ₂ O ₂ production	[132]
DC-CN	amylum	300W xenon lamp, λ>420 nm	Defect engineering	0 mg catalyst, 100 mL water, 10 vol% methanol	167.3 μmol·g ⁻¹ ·h ⁻¹	N ₂ fixation	[71]

6. Conclusions and outlook

Biomass-engineered g-C₃N₄ has emerged as a transformative green platform for addressing the three core intrinsic limitations of pristine g-C₃N₄: ultrafast photogenerated electron-hole recombination, narrow visible-light absorption range, and scarcity of surface-

active sites. Leveraging the unique structural and chemical merits of renewable biomass feedstocks including abundant reactive functional groups (hydroxyl, carboxyl, amino), hierarchical porous architectures, and tailorable molecular structures. Researcher have developed versatile modification strategies centered on hydrogen-bond engineering,

heterojunction construction, and defect engineering. These strategies substantially boost the photocatalytic performance toward H_2 evolution, H_2O_2 production, selective CO_2 reduction, organic pollutant degradation and N_2 fixation. Meanwhile, they realize high-value valorization of lignocellulosic biomass, thereby integrating sustainable resource utilization with green catalytic chemistry.

Despite remarkable progress in biomass-engineered g- C_3N_4 photocatalysts for solar energy conversion and environmental remediation, translating these laboratory achievements into stable, scalable, and industrially viable technologies still faces a series of profound and interrelated challenges. These bottlenecks mainly lie in precise structural control, unclear catalytic mechanisms, insufficient interfacial stability, and difficulties in large-scale preparation.

(i) The lack of precise structural and compositional control over biomass-derived functional motifs severely limits the rational optimization of g- C_3N_4 . Natural biomass exhibits inherent structural heterogeneity, batch-to-batch variability, and complex thermal decomposition behaviors during calcination, making it difficult to uniformly tailor surface functional groups, heteroatom doping concentrations, vacancy densities, and hierarchical pore architectures at the molecular level.^[133, 134] The random distribution of hydroxyl, carboxyl, and aromatic moieties often leads to uncontrolled structural collapse, partial agglomeration, or loss of active sites during in-situ polymerization, resulting in inconsistent photocatalytic performance and poor reproducibility across different preparations.^[135] Unlike well-defined synthetic modifiers, biomass cannot be easily fine-tuned to deliver targeted electronic modulation, impeding the establishment of clear structure activity relationships essential for predictive catalyst design.

(ii) The fundamental understanding of interfacial charge-transfer dynamics and intrinsic reaction mechanisms remains incomplete and largely phenomenological. While hydrogen-bonding interactions, heterojunction formation, and defect engineering are widely invoked to explain enhanced activity, direct in-situ observations of charge separation, migration pathways, and intermediate evolution at the biomass-engineered g- C_3N_4 interface are still scarce. Key questions persist. For example, how do hydrogen-bond networks precisely regulate the density of states and band alignment at the atomic scale? What are the exact roles of biomass-derived carbon bridges and nitrogen vacancies in promoting PCET or C-C coupling for CO_2 reduction to multi-carbon products? Without quantitative mechanistic

insights derived from operando characterization and high-fidelity theoretical simulations, the field relies heavily on empirical optimization rather than knowledge-driven design, slowing the development of next-generation catalysts with maximized quantum efficiency and product selectivity.

(iii) Interfacial stability and long-term durability under realistic operating conditions pose substantial limitations. The non-covalent interactions (e.g., hydrogen bonding, π - π stacking) that dominate biomass-engineered g- C_3N_4 coupling are susceptible to disruption under prolonged illumination, continuous aqueous immersion, or harsh redox environments, leading to gradual delamination, leaching of active components, and irreversible performance decay. Biomass-derived moieties may also undergo photo-oxidation or hydrolysis over extended cycling, reducing the density of active sites and compromising structural integrity. For industrial implementation, photocatalysts must maintain high activity over hundreds of hours without significant deactivation; yet, systematic studies on aging mechanisms, regeneration strategies, and stability thresholds for biomass-engineered g- C_3N_4 are largely absent, creating a critical gap between laboratory demonstrations and real-world applicability.

(iv) Limited performance in practical reaction systems and insufficient product selectivity restrict real-world utility. Many high-activity results are obtained under idealized conditions (e.g., pure water, sacrificial agents, concentrated simulated solar irradiation) that poorly mimic complex industrial or environmental matrices containing impurities, varying pH, and natural sunlight fluctuations. For gas-phase reactions such as CO_2 photoreduction, low selectivity toward high-value multi-carbon products (e.g., C_2H_6) remains a persistent challenge, with most systems favoring C_1 products or suffering from competitive H_2 evolution. Similarly, in pollutant degradation, incomplete mineralization and potential formation of toxic intermediates are rarely addressed, undermining the environmental benefits of photocatalytic remediation.

(v) The environmental footprint of biomass processing should be evaluated from a life-cycle assessment (LCA) perspective. Although biomass is renewable and abundant, its conversion into functional modifiers or carbonaceous components may involve energy-intensive pyrolysis/calcination, acid/base or oxidative pretreatment, solvent consumption, wastewater generation and downstream separation. Therefore, the real sustainability of biomass-engineered g- C_3N_4 should be judged not only by photocatalytic activity, but also by full-process indicators, including

biomass source and transportation, chemical and energy inputs, carbon emissions, solvent recovery, catalyst durability, recyclability and end-of-life treatment. Future studies should prioritize waste or low-value biomass feedstocks, mild aqueous/enzymatic pretreatment, low-temperature or solar-assisted synthesis, closed-loop solvent recovery and quantitative LCA benchmarking to avoid shifting environmental burdens from the application stage to the materials fabrication stage.

Collectively, to overcome these challenges, it is imperative to move beyond empirical trial-and-error and toward knowledge-based rational design of biomass-modified g-C₃N₄ photocatalysts. To unlock their full potential for large-scale sustainable applications in solar energy conversion and environmental remediation, future research should prioritize three transformative directions: (i) Develop machine learning frameworks to rapidly screen and quantitatively predict the optimal mass/volume

biomass-to-g-C₃N₄ feeding ratios, which can accelerate high-throughput catalyst screening and establish quantitative structure-activity relationships for predictive rational design and stable batch reproducibility; (ii) Customize and advance operando in situ characterization techniques capable of dynamically tracking real-time biomass pyrolysis, thermal decomposition, heteroatom doping evolution, and interfacial bonding rearrangement throughout the calcination process, to uncover hidden intermediate transformation mechanisms; (iii) Establish universal, standardized biomass pretreatment protocols covering raw biomass fractionation, purification, and mild activation workflows, to eliminate batch-to-batch compositional fluctuations and drastically improve the experimental repeatability of biomass-derived photocatalysts.

With an eye to the future, a great number of opportunities and challenges are presented for this booming and hot field (Fig. 18). We believe that this

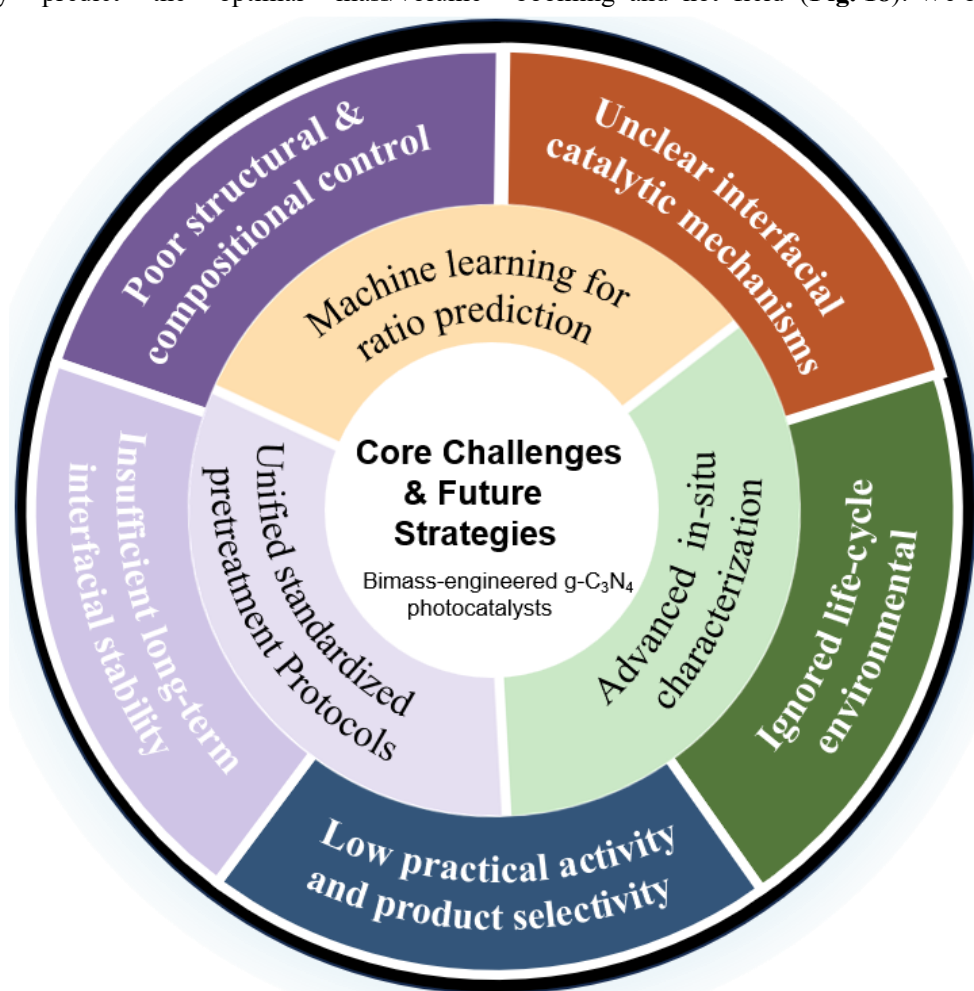


Fig. 18 Summary of core challenges and future strategies with biomass-engineered g-C₃N₄ photocatalysts. [30, 33, 35, 136 -140]

review article can provide important strategic guidance for the rational design and development of novel biomass-engineered g-C₃N₄ photocatalysts with high catalytic activity, excellent stability, efficient visible light utilization, environmental friendliness and low cost. It is expected that with the continuous innovation and technological breakthroughs in related fields, biomass-engineered g-C₃N₄ materials will break through the limitations of basic laboratory research, move towards large-scale practical applications. They will provide an integrated and coordinated solution for renewable energy development, ecological environment restoration and high-value utilization of biomass, helping to achieve the goals of green and low-carbon development.

CRediT author statement

Zhaoqiang Wang: Writing - review & editing, Writing - original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Xin Liu:** writing - review & editing, formal analysis. **Zihe Chen:** Conceptualization, Supervision, Writing - review & editing. **Yin Xiao:** Data curation, Li Shuai: Supervision, Writing - review & editing. **Yonghao Ni:** Supervision, Writing - review & editing. **Guangfu Liao:** Writing - review & editing, Supervision, Funding acquisition, Conceptualization.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 22578059), the Youth Talent Support Program of China Association for Science and Technology (Grant No. 2023QNRC0692), and the Natural Science Foundation of Fujian (Grant No. 2026J009033).

References

- [1] Zhaoqiang Wang, Guixiang Ding, Hongwei Huang, Juntao Zhang, Qi Lv, Li Shuai, Yonghao Ni, Guangfu Liao. Unraveling the dipole field in ultrathin, porous, and defective carbon nitride nanosheets for record-high piezo-photocatalytic H₂O₂ production. *eScience* 2025, 5 (3) 100370. <https://doi.org/10.1016/j.esci.2024.100370>.
- [2] Yuan Xue, Sheng Liu, Yujuan Guo, Yanjun Zhang, Zushun Xu, Yongxing Zhang, Guangfu Liao, Qing Li. Biomass-engineered graphitic carbon nitride: Structure modulation, charge dynamics, and photocatalytic applications. *Green Energy & Environment* 2026, <https://doi.org/10.1016/j.gee.2026.03.002>.
- [3] Qi Lv, Hao Lu, Xusheng Wang, Zhaoqiang Wang, Guixiang Ding, Ye Feng, Peng Wang, Qing Li, Haiyang Gao, Guangfu Liao. Photocatalysis over CdS quantum dots/oxygen doped g-C₃N₄ Z-scheme heterojunction: Revealing the synergistic effects of quantum confinement effect, defect engineering, and Z-scheme mechanism. *Chemical Engineering Journal* 2025, 524 169496. <https://doi.org/10.1016/j.cej.2025.169496>.
- [4] Phan Pham Duc Minh, Duc-Viet Nguyen, Minh Chien Nguyen, Nguyen Hoai Anh, Huynh Phuoc Toan, Pho Phuong Ly, Ngoc Linh Nguyen, Tiep Van Nguyen, Minh-Thuan Pham, Thuy Dieu Thi Ung, Do Danh Bich, Pham Thu Hue, Nguyen Thi Ngoc Hue, Van-Han Dang, Woo Jong Yu, Seung Hyun Hur, Quang Hung Nguyen, Luu Anh Tuyen, Hoai-Thanh Vuong. Promoted hydrogen peroxide production from pure water on g-C₃N₄ with nitrogen defects constructed through solvent-precursor interactions: Exploring a complex story in piezo-photocatalysis. *Small Methods* 2025, 9 (1) 2400797. <https://doi.org/10.1002/smt.202400797>.
- [5] Fangyi Li, Yulianti Anjarsari, Jiamei Wang, Rifda Azzahidah, Jizhou Jiang, Jing Zou, Kun Xiang, Huijuan Ma, Aramel. Modulation of the lattice structure of 2D carbon-based materials for improving photo/electric properties. *Carbon Letters* 2023, 33 (5) 1321-1331. <https://doi.org/10.1007/s42823-022-00380-4>.
- [6] Zhilei Chen, Zhaoxia Li, Yunjiang Yu, Mingdeng Xiang, Cheng Ding, Entian Cui, Jizhou Jiang. Unveiling the enhanced activity origin of BiOI-xCl/C₃N₅ photocatalyst in CO₂-to-CO directional conversion. *Chinese Chemical Letters* 2026, 37 (9) 112313. <https://doi.org/10.1016/j.ccl.2025.112313>.
- [7] Junlei Zhang, Guojia Yu, Chaoyang Yang, Wei Zhao, Zhiyao Duan, Hai Liu, Shijie Li. Reinforced ROS Generation and anti-photocorrosion for boosted photooxidation disinfection by IEF-enhanced type II charge carrier dynamics. *SusMat* 2025, 5 (2) e70002. <https://doi.org/10.1002/sus2.70002>.
- [8] Shijie Li, Rui Li, Kexin Dong, Yanping Liu, Xin Yu, Wenyao Li, Tong Liu, Zaiwang Zhao, Mingyi Zhang, Bin Zhang, Xiaobo Chen. Self-floating Bi₄O₅Br₂/P-doped C₃N₄/carbon fiber cloth with S-scheme heterostructure for boosted photocatalytic removal of emerging organic contaminants. *Chinese Journal of Catalysis* 2025, 76 37-49. [https://doi.org/10.1016/S1872-2067\(25\)64780-2](https://doi.org/10.1016/S1872-2067(25)64780-2).
- [9] Shijie Li, Xinyu Li, Yanping Liu, Peng Zhang, Junlei Zhang, Bin Zhang. Interfacial engineering of a plasmonic Ag/Ag₂CO₃/C₃N₅ S-scheme heterojunction for high-performance photocatalytic degradation of antibiotics. *Chinese Journal of Catalysis* 2025, 72 130-142. [https://doi.org/10.1016/S1872-2067\(25\)64652-3](https://doi.org/10.1016/S1872-2067(25)64652-3).
- [10] Entian Cui, Yulian Lu, Zhaoxia Li, Zhilei Chen, Chengyan Ge, Jizhou Jiang. Interfacial B-O bonding modulated S-scheme B-doped N-deficient C₃N₄/O-doped-C₃N₅ for efficient photocatalytic overall water splitting. *Chinese Chemical Letters* 2025, 36 (1) 110288. <https://doi.org/10.1016/j.ccl.2024.110288>.

- [11] Jizhou Jiang, Zhiguo Xiong, Haitao Wang, Guodong Liao, Saishuai Bai, Jing Zou, Pingxiu Wu, Peng Zhang, Xin Li. Sulfur-doped g-C₃N₄/g-C₃N₄ isotype step-scheme heterojunction for photocatalytic H₂ evolution. *Journal of Materials Science & Technology* 2022, 118 15-24. <https://doi.org/10.1016/j.jmst.2021.12.018>.
- [12] Jiahe Peng, Dongxiao Wen, Yilin Li, Xiaoxian Hu, Qian Zhou, Shuangshuang Huang, Yuandong Zhao, Weiping Gong, Jizhou Jiang. Boosting ultra-sensitive electrochemical sensing of uric acid through spatial extra oxygen coordination of Co-CN/Ti₃CN. *Science China Chemistry* 2026, 69 (1) 225-238. <https://doi.org/10.1007/s11426-025-2986-9>.
- [13] Jizhou Jiang, Lianglang Yu, Jiahe Peng, Weiping Gong, Wei Sun. Advance in the modification of g-C₃N₄-based composite for photocatalytic H₂ production. *Carbon Letters* 2025, 35 (2) 417-440. <https://doi.org/10.1007/s42823-024-00853-8>.
- [14] Haoyuan Yin, Biyang Zhang, Xiaomei Dai, Jinman Yang, Jizhou Jiang, Hui Xu. 3D printing technology for photocatalysis: review and prospect. *Composite Functional Materials* 2025, 1 (2) 20250205. <https://doi.org/10.63823/20250205>.
- [15] Haitao Wang, Jizhou Jiang, Lianglang Yu, Jiahe Peng, Zhou Song, Zhiguo Xiong, Neng Li, Kun Xiang, Jing Zou, Jyh-Ping Hsu, Tianyou Zhai. Tailoring advanced N-defective and S-doped g-C₃N₄ for photocatalytic H₂ evolution. *Small* 2023, 19 (28) 2301116. <https://doi.org/10.1002/sml.202301116>.
- [16] Xianghai Song, Huiling Zhao, Sheng Xu, Xiang Liu, Mei Wang, Xin Liu, Weiqiang Zhou, Jisheng Zhang, Yuanfeng Wu, Pengwei Huo. Hot electron back-injection from plasmonic Au nanoparticles boosts photocatalytic CO₂ reduction over boron-doped spherical g-C₃N₄. *Composite Functional Materials* 2026, 2 (1) 20260103. <https://doi.org/10.63823/20260103>.
- [17] Guangfu Liao, Yan Gong, Li Zhang, Haiyang Gao, Guan-Jun Yang, Baizeng Fang. Semiconductor polymeric graphitic carbon nitride photocatalysts: the "holy grail" for the photocatalytic hydrogen evolution reaction under visible light. *Energy & Environmental Science* 2019, 12 (7) 2080-2147. <https://doi.org/10.1039/C9EE00717B>.
- [18] Zhaoqiang Wang, Guixiang Ding, Juntao Zhang, Xianqing Lv, Peng Wang, Li Shuai, Chunxue Li, Yonghao Ni, Guangfu Liao. Critical role of hydrogen bonding between microcrystalline cellulose and g-C₃N₄ enables highly efficient photocatalysis. *Chemical Communications* 2024, 60 (2) 204-207. <https://doi.org/10.1039/D3CC04800D>.
- [19] Yu Qiao, Hao Lu, Xusheng Wang, Xiangxin Xue, Juan Jian, Zhuo Wang, Peng Wang, Guangfu Liao. Dual S-scheme charge transfer pathway in g-C₃N₄ quantum dots/HKUST-1/TiO₂ ternary heterojunctions for photocatalytic pollutant degradation. *Inorganic Chemistry* 2025, 64 (42) 21212-21226. <https://doi.org/10.1021/acs.inorgchem.5c03972>.
- [20] Jizhou Jiang, Yanghanbin Zhang, Wei Sun, Jiahe Peng, Weilong Shi, Yang Qu, Enzhou Liu, Arramel, Zhiliang Jin. A review of updated red phosphorus-based photocatalysts. *Composite Functional Materials* 2025, 1 (1) 20250101. <https://doi.org/10.63823/20250101>.
- [21] Lijing Wang, Tianyi Yang, Bo Feng, Xiangyu Xu, Yuying Shen, Zihan Li, Arramel, Jizhou Jiang. Constructing dual electron transfer channels to accelerate CO₂ photoreduction guided by machine learning and first-principles calculation. *Chinese Journal of Catalysis* 2023, 54 265-277. [https://doi.org/10.1016/S1872-2067\(23\)64546-2](https://doi.org/10.1016/S1872-2067(23)64546-2).
- [22] Xin Liu, Guixiang Ding, Xingzhe Guo, Xusheng Wang, Zhaoqiang Wang, Zihe Chen, Yin Xiao, Li Shuai, Guangfu Liao. Synergizing Donor-acceptor Ni-MOF with lignin proton relay for efficient and selective CO₂-to-CO photoreduction. *Advanced Materials* 2026, 38 (9) e20384. <https://doi.org/10.1002/adma.202520384>.
- [23] Tianshang Shan, Jiahu Li, Shengye Wu, Hui Wu, Fengshan Zhang, Guangfu Liao, He Xiao, Liulian Huang, Lihui Chen. Boosting H₂O₂ production over carboxymethyl cellulose modified g-C₃N₄ via hydrogen-bonding-assisted charge transfer. *Chemical Engineering Journal* 2023, 478 147509. <https://doi.org/10.1016/j.cej.2023.147509>.
- [24] Juan Liu, Yang Liu, Naiyun Liu, Yuzhi Han, Xing Zhang, Hui Huang, Yeshayahu Lifshitz, Shuit-Tong Lee, Jun Zhong, Zhenhui Kang. Metal-free efficient photocatalyst for stable visible water splitting via a two-electron pathway. *Science* 2015, 347 (6225) 970-974. <https://doi.org/10.1126/science.aaa3145>.
- [25] Yingfei Wang, Fengliang Wang, Yiping Feng, Zhijie Xie, Qianxin Zhang, Xiaoyu Jin, Haijin Liu, Yang Liu, Wenying Lv, Guoguang Liu. Facile synthesis of carbon quantum dots loaded with mesoporous g-C₃N₄ for synergistic absorption and visible light photodegradation of fluoroquinolone antibiotics. *Dalton Transactions* 2018, 47 (4) 1284-1293. <https://doi.org/10.1039/C7DT04360K>.
- [26] Zhaoqiang Wang, Guixiang Ding, Chunxue Li, Hongwei Huang, Yin Xiao, Zihe Chen, Juntao Zhang, He Xiao, Zhuan Wang, Lihui Chen, Li Shuai, Yonghao Ni, Guangfu Liao. Hydrogen-bonds bridged biomass-assisted S-scheme junction boosts proton-coupled electron transfer for H₂O₂ photosynthesis. *eScience* 2026, 100562. <https://doi.org/10.1016/j.esci.2026.100562>.
- [27] Zihe Chen, Guixiang Ding, Zhaoqiang Wang, Yin Xiao, Xin Liu, Lihui Chen, Chunxue Li, Hongwei Huang, Guangfu Liao. Precision molecular engineering of carbon nitride for efficient and selective photoreduction of CO₂ to C₂H₆ in pure water. *Advanced Functional Materials* 2025, 35 (25) 2423213. <https://doi.org/10.1002/adfm.202423213>.
- [28] Qiang Chen, Xiaofei Tan, Yunguo Liu, Shaobo Liu, Meifang Li, Yanling Gu, Peng Zhang, Shujing Ye, Zhongzhu Yang, Yuanyuan Yang. Biomass-derived porous graphitic carbon materials for energy and environmental applications. *Journal of Materials Chemistry A* 2020, 8 (12) 5773-5811. <https://doi.org/10.1039/C9TA11618D>.
- [29] Jizhou Jiang, Neng Li, Jing Zou, Xing Zhou, Goki Eda,

- Qingfu Zhang, Hua Zhang, Lain-Jong Li, Tianyou Zhai, Andrew T. S. Wee. Synergistic additive-mediated CVD growth and chemical modification of 2D materials. *Chemical Society Reviews* 2019, 48 (17) 4639-4654. <https://doi.org/10.1039/c9cs00348g>.
- [30] Neng Li, Yufei Yang, Zuhao Shi, Zhigao Lan, Arramel Arramel, Peng Zhang, Wee-Jun Ong, Jizhou Jiang, Jianfeng Lu. Shedding light on the energy applications of emerging 2D hybrid organic-inorganic halide perovskites. *iScience* 2022, 25 (2) <https://doi.org/10.1016/j.isci.2022.103753>.
- [31] Jizhou Jiang, Fangyi Li, Jing Zou, Song Liu, Jiamei Wang, Yilun Zou, Kun Xiang, Han Zhang, Guoyin Zhu, Yizhou Zhang, Xianzhu Fu, Jyh-Ping Hsu. Three-dimensional MXenes heterostructures and their applications. *Science China Materials* 2022, 65 (11) 2895-2910. <https://doi.org/10.1007/s40843-022-2186-0>.
- [32] Fangyi Li, Jizhou Jiang, Jiamei Wang, Jing Zou, Wei Sun, Haitao Wang, Kun Xiang, Pingxiu Wu, Jyh-Ping Hsu. Porous 3D carbon-based materials: An emerging platform for efficient hydrogen production. *Nano Research* 2023, 16 (1) 127-145. <https://doi.org/10.1007/s12274-022-4799-z>.
- [33] Ning Song, Jizhou Jiang, Shihuan Hong, Yun Wang, Chunmei Li, Hongjun Dong. State-of-the-art advancements in single atom electrocatalysts originating from MOFs for electrochemical energy conversion. *Chinese Journal of Catalysis* 2024, 59 38-81. [https://doi.org/10.1016/S1872-2067\(23\)64622-4](https://doi.org/10.1016/S1872-2067(23)64622-4).
- [34] Fangyi Li, Guihua Zhu, Jizhou Jiang, Lang Yang, Fengxia Deng, Arramel, Xin Li. A review of updated S-scheme heterojunction photocatalysts. *Journal of Materials Science & Technology* 2024, 177 142-180. <https://doi.org/10.1016/j.jmst.2023.08.038>.
- [35] Jizhou Jiang, Fangyi Li, Lei Ding, Chengxun Zhang, Arramel, Xin Li. MXenes/CNTs-based hybrids: Fabrications, mechanisms, and modification strategies for energy and environmental applications. *Nano Research* 2024, 17 (5) 3429-3454. <https://doi.org/10.1007/s12274-023-6302-x>.
- [36] Fengxia Deng, Jizhou Jiang, Ignasi Sirés. State-of-the-art review and bibliometric analysis on electro-fenton process. *Carbon Letters* 2023, 33 (1) 17-34. <https://doi.org/10.1007/s42823-022-00420-z>.
- [37] Hanghang Zhou, Wenqiang Ye, Jizhou Jiang, Zheng Wang. Recent advances on surface modification of non-oxide photocatalysts towards efficient CO₂ conversion. *Carbon Letters* 2024, 34 (6) 1569-1591. <https://doi.org/10.1007/s42823-024-00748-8>.
- [38] Bo Feng, Yanan Liu, Kun Wan, Sijie Zu, Yan Pei, Xiaoxin Zhang, Minghua Qiao, Hexing Li, Baoning Zong. Tailored exfoliation of polymeric carbon nitride for photocatalytic H₂O₂ production and CH₄ valorization mediated by O₂ activation. *Angewandte Chemie International Edition* 2024, 63 (18) e202401884. <https://doi.org/10.1002/anie.202401884>.
- [39] Wenwen Cao, Tao Hu, Yuanyuan Zhao, Zhenglin Li, Yichan Hu, Cuncheng Li, Yiqiang Sun, Feng Ding, Guojin Liang. Tailoring C₃N₄ host to enable a high-loading iodine electrode for high energy and long cycling Zn-iodine battery. *ACS Energy Letters* 2025, 10 (1) 320-329. <https://doi.org/10.1021/acsenergylett.4c02930>.
- [40] Shihai Cao, Hao Liu, Zhenhe Jia, Meng Guo, Wentong Gao, Zhaohan Ding, Weijie Yang, Liang Chen, Wenjing Wang. Controllable adsorption groups on amine-functionalized carbon nitride for enhanced photocatalytic CO₂ reduction. *Chemical Engineering Journal* 2023, 455 140746. <https://doi.org/10.1016/j.cej.2022.140746>.
- [41] Yong-Jun Yuan, Zhikai Shen, Shiting Wu, Yibing Su, Lang Pei, Zhenguo Ji, Mingye Ding, Wangfeng Bai, Yifan Chen, Zhen-Tao Yu, Zhigang Zou. Liquid exfoliation of g-C₃N₄ nanosheets to construct 2D-2D MoS₂/g-C₃N₄ photocatalyst for enhanced photocatalytic H₂ production activity. *Applied Catalysis B: Environmental* 2019, 246 120-128. <https://doi.org/10.1016/j.apcatb.2019.01.043>.
- [42] Katharina Schwinghammer, Maria B. Mesch, Viola Duppel, Christian Ziegler, Jürgen Senker, Bettina V. Lotsch. Crystalline carbon nitride nanosheets for improved visible-light hydrogen evolution. *Journal of the American Chemical Society* 2014, 136 (5) 1730-1733. <https://doi.org/10.1021/ja411321s>.
- [43] Xu Zhang, Hui Su, Peixin Cui, Yongyong Cao, Zhenyuan Teng, Qitao Zhang, Yang Wang, Yibo Feng, Ran Feng, Jixiang Hou, Xiyuan Zhou, Peijie Ma, Hanwen Hu, Kaiwen Wang, Cong Wang, Liyong Gan, Yunxuan Zhao, Qinghua Liu, Tierui Zhang, Kun Zheng. Developing Ni single-atom sites in carbon nitride for efficient photocatalytic H₂O₂ production. *Nature Communications* 2023, 14 (1) 7115. <https://doi.org/10.1038/s41467-023-42887-y>.
- [44] Youqing Yang, Jiwei Shi, Chenguang Liu, Qiong Liu, Jian Yang, Xiaogang Tong, Jiong Lu, Jie Wu. Engineered polymeric carbon nitride for photocatalytic diverse functionalization of electronic-rich alkenes. *Angewandte Chemie International Edition* 2025, 64 (5) e202417099. <https://doi.org/10.1002/anie.202417099>.
- [45] Nan Zheng, Binqiu Duan, Xiankang Niu, Xinyi Sun, Changqing Zhao, Jitao Lu, Xiaomei Zhang. A multifunctional and self-adaptive hydrogel with on-demand bactericidal/anti-inflammatory for synergistic multi-enzyme-H₂ therapy and monitoring of diabetic wounds. *Advanced Functional Materials* 2026, 36 (42) e24084. <https://doi.org/10.1002/adfm.202524084>.
- [46] Hao Liu, Bin Yang, Guangfu Liao, Baoyu Huang, Jun Li, Raul D. Rodriguez, Xin Jia. Facilitating carrier kinetics in ultrathin porous carbon nitride through shear-repair strategy for peroxymonosulfate-assisted water purification. *Nature Communications* 2025, 16 (1) 5909. <https://doi.org/10.1038/s41467-025-61185-3>.
- [47] Lihao Mao, Binjiang Zhai, Jinwen Shi, Xing Kang, Bingru Lu, Yanbing Liu, Cheng Cheng, Hui Jin, Eric Lichtfouse,

- Liejn Guo. Supercritical CH₃OH-triggered isotype heterojunction and groups in g-C₃N₄ for enhanced photocatalytic H₂ evolution. *ACS Nano* 2024, 18 (21) 13939-13949. <https://doi.org/10.1021/acsnano.4c03922>.
- [48] Zhimin Zhai, Huihui Zhang, Fushuang Niu, Peiyang Liu, Jiajia Zhang, Hongbin Lu. Mesoporous carbon nitride with π -electron-rich domains and polarizable hydroxyls fabricated via solution thermal shock for visible-light photocatalysis. *ACS Nano* 2022, 16 (12) 21002-21012. <https://doi.org/10.1021/acsnano.2c08643>.
- [49] Yongkang Quan, Ruidong Li, Yunfei Yang, Rongxing Chen, Xinhuan Lin, Jianying Huang, Yun Hau Ng, Yuekun Lai. Localized asymmetric carbon nitride with tailored electronic traps: modulating charge kinetics to promote efficient light-driven H₂O₂ production. *Advanced Functional Materials* 2026, 36 (46) e75360. <https://doi.org/10.1002/adfm.75360>.
- [50] Qi Li, Yanqing Jiao, Yunqi Tang, Jing Zhou, Baogang Wu, Baojiang Jiang, Honggang Fu. Shear stress triggers ultrathin-nanosheet carbon nitride assembly for photocatalytic H₂O₂ production coupled with selective alcohol oxidation. *Journal of the American Chemical Society* 2023, 145 (38) 20837-20848. <https://doi.org/10.1021/jacs.3c05234>.
- [51] Nithinraj Panangattu Dharmarajan, Mohammed Fawaz, Jae-Hun Yang, Matej Huš, Xuan Minh Chau Ta, Ayona K. Jose, Vibin Perumalsamy, Aathira M. Sadanandan, C. I. Sathish, Blaž Likozar, Byoung-Hwa Lee, Chung-Hwan Jeon, Antonio Tricoli, Ajayan Vinu. Supramolecularly directed confined crystallization of lamellar carbon nitride for efficient photocatalytic Hydrogen Generation. *Advanced Energy Materials* 2026, 16 (22) e70908. <https://doi.org/10.1002/aenm.70908>.
- [52] Aathira M. Sadanandan, Mohammed Fawaz, Nithinraj Panangattu Dharmarajan, Matej Huš, Gurwinder Singh, C. I. Sathish, Blaž Likozar, Zhixuan Li, Ajanya M. Ruban, Chung-Hwan Jeon, Jae-Hun Yang, Prashant Kumar, Ajayan Vinu. Mesoporous C-doped C₃N₅ as a superior photocatalyst for CO₂ reduction. *Applied Catalysis B: Environment and Energy* 2025, 362 124701. <https://doi.org/10.1016/j.apcatb.2024.124701>.
- [53] Jolitta Sheri John Britto, Thi Kim Anh Tran, Vibin Perumalsamy, C. I. Sathish, Sharon L. Wong, Gurwinder Singh, Bjørnar Arstad, Chandramathy Surendran Praveen, Prashant Kumar, Ajayan Vinu. Antibacterial performance of copper-loaded mesoporous C₃N₆. *Small* 2026, 22 (13) e13990. <https://doi.org/10.1002/sml.202513990>.
- [54] Zhen Cao, Weijie Zhang, Yuying Li, Junnan Qu, Jingxuan Ren, Yinghua Zhang, Jinhao Chen, Jiahao Lei, Jingyao Li, Xinli Guo. C₃N₄ template-based N-doped porous carbon cathode for zinc-ion hybrid capacitors. *ACS Applied Nano Materials* 2024, 7 (21) 24778-24787. <https://doi.org/10.1021/acsanm.4c04677>.
- [55] Jinqiang Zhang, Yunguo Li, Xiaoli Zhao, Huayang Zhang, Liang Wang, Haijun Chen, Shuaijun Wang, Xinyuan Xu, Lei Shi, Lai-Chang Zhang, Jean-Pierre Veder, Shiyong Zhao, Gareth Nealon, Mingbo Wu, Shaobin Wang, Hongqi Sun. A hydrogen-initiated chemical epitaxial growth strategy for in-plane heterostructured photocatalyst. *ACS Nano* 2020, 14 (12) 17505-17514. <https://doi.org/10.1021/acsnano.0c07934>.
- [56] Al Mojahid Afridi, Mahbuba Aktary, Syed Shaheen Shah, Sharif Iqbal Mitu Sheikh, Gazi Jahirul Islam, M. Nasiruzzaman Shaikh, Md Abdul Aziz. Advancing electrical engineering with biomass-derived carbon materials: applications, innovations, and future directions. *The Chemical Record* 2024, 24 (12) e202400144. <https://doi.org/10.1002/tcr.202400144>.
- [57] Ruibin Wang, Youguang Feng, Dongqi Li, Kaixin Li, Yong Yan. Towards the sustainable production of biomass-derived materials with smart functionality: a tutorial review. *Green Chemistry* 2024, 26 (16) 9075-9103. <https://doi.org/10.1039/D4GC01771D>.
- [58] Jianwen Zhou, Tianshang Shan, Fengshan Zhang, Bruno Boury, Liulian Huang, Yingkui Yang, Guangfu Liao, He Xiao, Lihui Chen. A novel dual-channel carbon nitride homojunction with nanofibrous carbon for significantly boosting photocatalytic hydrogen peroxide production. *Advanced Fiber Materials* 2024, 6 (2) 387-400. <https://doi.org/10.1007/s42765-023-00354-9>.
- [59] Ren Zou, Zhongxin Chen, Linxin Zhong, Wu Yang, Tingzhen Li, Jianyun Gan, Yunyi Yang, Zehong Chen, Haihong Lai, Xuehui Li, Chuanfu Liu, Shimelis Admassie, Emmanuel Iheanyichukwu Iwuoha, Jun Lu, Xinwen Peng. Nanocellulose-assisted molecularly engineering of nitrogen deficient graphitic carbon nitride for selective biomass photo-oxidation. *Advanced Functional Materials* 2023, 33 (29) 2301311. <https://doi.org/10.1002/adfm.202301311>.
- [60] Shan Liu, Ting Xu, Liyu Zhu, Kefeng Liu, Xingxiang Ji, Zhanhui Yuan, Chuanling Si. Highly compressible ultra-light 3D cellulose/graphene/carbon nitride aerogel for enhanced photocatalytic activity. *Chemical Engineering Journal* 2025, 503 158564. <https://doi.org/10.1016/j.cej.2024.158564>.
- [61] Xuejiao Wu, Nengchao Luo, Shunji Xie, Haikun Zhang, Qinghong Zhang, Feng Wang, Ye Wang. photocatalytic transformations of lignocellulosic biomass into chemicals. *Chemical Society Reviews* 2020, 49 (17) 6198-6223. <https://doi.org/10.1039/D0CS00314J>.
- [62] Qiaoran Liu, Hao Tian, Zhenghua Dai, Hongqi Sun, Jian Liu, Zhimin Ao, Shaobin Wang, Chen Han, Shaomin Liu. Nitrogen-doped carbon nanospheres-modified graphitic carbon nitride with outstanding photocatalytic activity. *Nano-Micro Letters* 2020, 12 (1) 24. <https://doi.org/10.1007/s40820-019-0358-x>.
- [63] Ying Xu, Wei Li, Ting Xu, Guanhua Wang, Weiwei Huan, Chuanling Si. Straightforward fabrication of lignin-derived carbon-bridged graphitic carbon nitride for improved visible photocatalysis of tetracycline hydrochloride assisted by peroxymonosulfate activation. *Advanced Composites and*

- hybrid Materials* 2023, 6 (6) 197. <https://doi.org/10.1007/s42114-023-00779-1>.
- [64] Yue Zhao, Zhen Wang, Xinrui Wang, Pingli Sun, Fanyao Meng, Guihua Yang, Xiaomeng Zhou, Jianing Wang, Xinjian Zhang, Gaojin Lyu. Construction of lignin-assisted nitrogen defective engineering graphitic carbon nitride for HMF selective conversion to maleic acid through photo-thermal processes. *Advanced Functional Materials* 2025, 35 (25) 2422264. <https://doi.org/10.1002/adfm.202422264>.
- [65] Guohua Dong, Weimeng Chi, Dong-feng Chai, Zhuanfang Zhang, Jinlong Li, Ming Zhao, Wenzhi Zhang, Jun Lv, Shijie Chen. A novel Ag₃BiO₃/ZnO/BC composite with abundant defects and utilizing hemp BC as charge transfer mediator for photocatalytic degradation of levofloxacin. *Applied Surface Science* 2023, 619 156732. <https://doi.org/10.1016/j.apsusc.2023.156732>.
- [66] Juan Liu, Ren Zou, Hao Zhang, Youzhi Song, Yunpeng Liu, Shilian Yang, Ruidong Xia, Emmanuel Iheanyichukwu Iwuoha, Usisipho Feleni, Shimelis Admassie, Xinwen Peng. Enhanced π -electron transport in graphitic carbon nitride (g-C₃N₄) by constructing biochar-welded donor-acceptor (D-A) configuration for photocatalytic conversion of biomass. *Applied Catalysis B: Environment and Energy* 2024, 357 124312. <https://doi.org/10.1016/j.apcatb.2024.124312>.
- [67] Man Luo, Lixia Qin, Jianwei Tao, Xue Gao, Taiyang Zhang, Shi-Zhao Kang, Xiangqing Li. Selective surface enhanced Raman detection and effective photocatalytic degradation of sulfonamides antibiotic based on a flexible three-dimensional chitosan/carbon nitride/silver substrate. *Journal of Hazardous Materials* 2023, 459 132131. <https://doi.org/10.1016/j.jhazmat.2023.132131>.
- [68] Haoxian Wang, Junjie Wang, Jin Xu, Jingkai Lin, Zhongshuai Zhu, Yazhi Liu, Feihu Mu, Bin Huang, Fei Yu, Chenmin Xu, Shaogui Yang, Huan He, Shaomin Liu, Shaobin Wang, Wenjie Tian. Spirulina-derived atomically dispersed Fe-N₄ sites on g-C₃N₄ for efficient CO₂ photoreduction. *Chemical Engineering Journal* 2025, 522 167048. <https://doi.org/10.1016/j.cej.2025.167048>.
- [69] Li Yang, Wei Zhou, Mingsong Dou, Xue Yue, Yongzheng Hu, Taiping Lu, Yu He, Yingying Du, Anning Zhu, Haokai Yang, Shaolin Lu, Xudong Chen. Conjugated polyelectrolytes/sucrose-doped hydroxyl-rich carbon nitride heterojunctions for photocatalytic hydrogen evolution: morphology control, interfacial modulation, and energy band engineering. *Advanced Functional Materials* 2025, 35 (41) 2500415. <https://doi.org/10.1002/adfm.202500415>.
- [70] Zihé Chen, Di Yan, Xusheng Wang, Guixiang Ding, Zhaoqiang Wang, Yin Xiao, Xin Liu, Peng Wang, Lihui Chen, Li Shuai, Guangfu Liao. Biochar-tailored carbon nitride enables piezo-photocatalytic H₂O₂ production via boosted charge transport. *ACS Catalysis* 2025, 15 (15) 13568-13580. <https://doi.org/10.1021/acscatal.5c02889>.
- [71] Zheng Tang, Lijun Xiong, Xiaoyue Zhang, Jinyou Shen, Aiwu Sun, Xiangyang Lin, Yong Yang. Biomass-induced diphasic carbon decoration for carbon nitride: band and electronic engineering targeting efficient N₂ photofixation. *Small* 2022, 18 (2) 2105217. <https://doi.org/10.1002/sml.202105217>.
- [72] Qi Li, Siyu Zhao, Baojiang Jiang, Mietek Jaroniec, Liping Zhang. Engineering defects in graphitic carbon nitride photocatalysts. *Materials Today* 2024, 80 886-904. <https://doi.org/10.1016/j.mattod.2024.09.019>.
- [73] Qinghua Liang, Zhi Li, Yu Bai, Zheng-Hong Huang, Feiyu Kang, Quan-Hong Yang. A composite polymeric carbon nitride with *in situ* formed isotype heterojunctions for highly improved photocatalysis under visible light. *Small* 2017, 13 (9) 1603182. <https://doi.org/10.1002/sml.201603182>.
- [74] Yunfeng Li, Zhiling Xia, Qing Yang, Linxi Wang, Yan Xing. Review on g-C₃N₄-based S-scheme heterojunction photocatalysts. *Journal of Materials Science & Technology* 2022, 125 128-144. <https://doi.org/10.1016/j.jmst.2022.02.035>.
- [75] Chunxue Li, Hao Lu, Guixiang Ding, Qing Li, Guangfu Liao. Recent advances on g-C₃N₄-based Z-scheme photocatalysts for organic pollutant removal. *Catalysis Science & Technology* 2023, 13 (10) 2877-2898. <https://doi.org/10.1039/D3CY00242J>.
- [76] Juntao Zhang, Di Yan, Guixiang Ding, Xusheng Wang, Chunxue Li, Sheng Zhong, Yaqin Yu, Li Shuai, Guangfu Liao. Dual Co sites in n-n type heterojunction enable selective electrochemical co-valorization of HMF and CO₂. *Angewandte Chemie International Edition* 2025, 64 (37) e202511448. <https://doi.org/10.1002/anie.202511448>.
- [77] Siyu Zhou, Jiaming Wu, Keyan Li, Chunshan Song, Xinwen Guo. Sulfur-defect-rich Bi₂S₃/ZnIn₂S₄ Z-scheme heterojunction for highly efficient H₂O₂ photosynthesis in pure water. *Chemical Synthesis* 2026, 6 (2) 32. <https://doi.org/10.20517/cs.2025.90>.
- [78] Muhammad Sohail, Sana Rauf, Muhammad Irfan, Asif Hayat, Majed M. Alghamdi, Adel A. El-Zahhar, Djamel Ghernaout, Yas Al-Hadeethi, Weiqiang Lv. Recent developments, advances and strategies in heterogeneous photocatalysts for water splitting. *Nanoscale Advances* 2024, 6 (5) 1286-1330. <https://doi.org/10.1039/D3NA00442B>.
- [79] Alberto Puga. photocatalytic Hydrogen production in the context of sustainable energy. In *photocatalytic hydrogen production for sustainable energy*, 2023; pp 1-18. <https://doi.org/10.1002/9783527835423>.
- [80] Abdulrahman S. Alotabi, Rohul H. Adnan, Abdulaziz M. Almutairi, Tokuhisa Kawawaki, Yuichi Negishi, Gregory F. Metha, Kazunari Domen, Gunther G. Andersson. A comprehensive review of the role of overlayers in photocatalytic overall water splitting and related reactions. *Chemical Reviews* 2026, 126 (5) 2801-2845. <https://doi.org/10.1021/acs.chemrev.5c00326>.
- [81] Chunxue Li, Guixiang Ding, Peng Wang, Kun Liu, Bin Yang, Guangfu Liao. Emerging frontiers of nickel-aluminium

- layered double hydroxide heterojunctions for photocatalysis. *Dalton Transactions* 2025, 54 (3) 889-897. <https://doi.org/10.1039/D4DT03141E>.
- [82] Guangfu Liao, Chunxue Li, Shi-Yong Liu, Baizeng Fang, Huaming Yang. Z-scheme systems: From fundamental principles to characterization, synthesis, and photocatalytic fuel-conversion applications. *Physics Reports* 2022, 983 1-41. <https://doi.org/10.1016/j.physrep.2022.07.003>.
- [83] Jiaxin Lin, Qizhi Gao, Xinlong Zheng, Jiadi Zhai, Fan Yang, Xinjie Chen, Minghui Wang, Miaomiao Yang, Jing Li, Xiaodong Shi, Yonghao Xiao, Xinlong Tian, Yuhao Liu. ZnIn₂S₄-based S-scheme heterojunction photocatalysts for efficient photocatalytic hydrogen evolution. *Coordination Chemistry Reviews* 2026, 559 217844. <https://doi.org/10.1016/j.ccr.2026.217844>.
- [84] Jiadi Zhai, Jiaxin Lin, Fan Yang, Jing Li, Xiaodong Shi, Yonghao Xiao, Xinlong Tian, Yuhao Liu. CuInS₂-based S-scheme heterojunction photocatalysts for efficient photocatalytic hydrogen evolution. *Coordination Chemistry Reviews* 2026, 563 218025. <https://doi.org/10.1016/j.ccr.2026.218025>.
- [85] Xinchun Wang, Kazuhiko Maeda, Arne Thomas, Kazuhiro Takanabe, Gang Xin, Johan M. Carlsson, Kazunari Domen, Markus Antonietti. A metal-free polymeric photocatalyst for hydrogen production from water under visible light. *Nature Materials* 2009, 8 (1) 76-80. <https://doi.org/10.1038/nmat2317>.
- [86] Guanyu Wu, Wei Zhang, Zhao Mo, Xinyu Zhao, Peipei Sun, Qiheng Wang, Pengcheng Yan, Xiaojie She, Hui Xu. S-Scheme Homojunction carbon nitride for photocatalytic Overall Water Splitting. *ACS Catalysis* 2025, 15 (11) 8822-8832. <https://doi.org/10.1021/acscatal.5c01086>.
- [87] Guanyu Wu, Xue Gao, Peipei Sun, Zhao Mo, Qiheng Wang, Hanxiang Chen, Henghui Liao, Pengcheng Yan, Xiaojie She, Hui Xu. High-intensity interfacial electric fields between co-catalysts and semiconductor: A determinant factor in enhancing photocatalytic hydrogen production. *Applied Catalysis B: Environment and Energy* 2025, 371 125265. <https://doi.org/10.1016/j.apcatb.2025.125265>.
- [88] Rui-Zhe Wang, Zhi Lin, Yi-Qing Wang, Kai-Ni Zhang, Ge-Hong Zhang, Jie Zhang, Samuel S. Mao, Shao-Hua Shen. A direct polymeric carbon nitride/tungsten oxide Z-scheme heterostructure for efficient photocatalytic hydrogen generation via reforming of plastics into value-added chemicals. *Rare Metals* 2024, 43 (8) 3771-3783. <https://doi.org/10.1007/s12598-024-02714-9>.
- [89] Ikram Ullah, Ning Qin, Pei Zhao, Jing-Han Li, Shuai Chen, An-Wu Xu. Improved charge separation and transport with l-aspartic acid derived carbon-doped g-C₃N₄ for efficient visible-light photocatalytic H₂ production. *Sustainable Energy & Fuels* 2024, 8 (24) 5868-5876. <https://doi.org/10.1039/D4SE01264J>.
- [90] Qiang Gao, Zhengzheng Xie, Xiaohong Shang, Sajjad Hussain, Jianjun Yang, Xianwei Fu, Ruifeng Zhou, Yaping Yan, Qiuye Li. In situ composite of biomass derived carbon/porous carbon nitride and its enhanced performance in solar-driven photocatalytic hydrogen evolution reaction. *Solar Energy* 2024, 283 113019. <https://doi.org/10.1016/j.solener.2024.113019>.
- [91] Bin Yang, Xiaolong Li, Qian Zhang, Xiaodong Yang, Jianguo Wan, Guangfu Liao, Jiaojiao Zhao, Rongjie Wang, Jichang Liu, Raul D. Rodriguez, Xin Jia. Ultrathin porous carbon nitride nanosheets with well-tuned band structures via carbon vacancies and oxygen doping for significantly boosting H₂ production. *Applied Catalysis B: Environmental* 2022, 314 121521. <https://doi.org/10.1016/j.apcatb.2022.121521>.
- [92] Si Deng, Weiping Xiong, Gaoxia Zhang, Guangfu Wang, Yongxi Chen, Wenjun Xiao, Qingkai Shi, Ao Chen, Huayue Kang, Min Cheng, Yang Liu, Jun Wang. Metal-free modification overcomes the photocatalytic limitations of graphitic carbon nitride: efficient production and in situ application of hydrogen peroxide. *Advanced Energy Materials* 2024, 14 (39) 2401768. <https://doi.org/10.1002/aenm.202401768>.
- [93] Xinyu Zou, Qingkai Shi, Min Cheng, Danlian Huang, Gaoxia Zhang, Wenjun Wang, Guangfu Wang, Hongda Liu, Yongxi Chen, Ao Chen, Si Deng. Metal-organic framework-based materials for photocatalytic hydrogen peroxide production: insights into mechanism, modification strategies, and environmental applications. *Advanced Energy Materials* 2025, 15 (30) 2501424. <https://doi.org/10.1002/aenm.202501424>.
- [94] Tengyang Gao, Degui Zhao, Saisai Yuan, Ming Zheng, Xianjuan Pu, Liang Tang, Zhendong Lei. Energy band engineering of graphitic carbon nitride for photocatalytic hydrogen peroxide production. *Carbon Energy* 2024, 6 (11) e596. <https://doi.org/10.1002/cey2.596>.
- [95] Huazhang Guo, Li Zhou, Kai Huang, Yongqiang Li, Weidong Hou, Huang Liao, Cheng Lian, Siwei Yang, Deli Wu, Zhendong Lei, Zheng Liu, Liang Wang. Nitrogen-rich carbon dot-mediated n→π* electronic transition in carbon nitride for superior photocatalytic hydrogen peroxide production. *Advanced Functional Materials* 2024, 34 (38) 2402650. <https://doi.org/10.1002/adfm.202402650>.
- [96] Hongjie Zhu, Yikai Yang, Minghui Li, Luning Zou, Haitao Zhao. photocatalytic in situ H₂O₂ production and activation for enhanced ciprofloxacin degradation over CeO₂-Co₃O₄/g-C₃N₄: key role of CeO₂. *Rare Metals* 2024, 43 (6) 2695-2707. <https://doi.org/10.1007/s12598-023-02583-8>.
- [97] Guangfu Liao, Guixiang Ding, Bin Yang, Chunxue Li. Challenges in photocatalytic carbon dioxide reduction. *Precision Chemistry* 2024, 2 (2) 49-56. <https://doi.org/10.1021/prechem.3c00112>.
- [98] Yin Xiao, Guixiang Ding, Jiayu Tao, Zhaoqiang Wang, Ziheng Chen, Lihui Chen, Li Shuai, Guangfu Liao. Selective conversion of CO₂ to C₂H₆ in pure water photocatalyzed by

- fluorobenzene-linked perylene diimide. *Nature Communications* 2025, 16 (1) 7476. <https://doi.org/10.1038/s41467-025-62369-7>.
- [99] Kun Liu, Muhammad Asif Nawaz, Guangfu Liao. Progress and future challenges in designing high-performance Ni/CeO₂ catalysts for CO₂ methanation: A critical review. *Carbon Neutralization* 2025, 4 (1) e190. <https://doi.org/10.1002/cn2.190>.
- [100] Guixiang Ding, Zhaoqiang Wang, Ziheng Chen, Yin Xiao, Xin Liu, Li Shuai, Lihui Chen, Hongwei Huang, Guangfu Liao. Unsaturated coordination-regulated high-spin nickel sites for selective solar-driven carbon dioxide conversion in pure water. *Energy & Environmental Science* 2026, 19 (2) 486-495. <https://doi.org/10.1039/D5EE04331J>.
- [101] Ziheng Chen, Yin Xiao, Xin Liu, Hao Lu, Xusheng Wang, Guixiang Ding, Zhaoqiang Wang, Peng Wang, Guangfu Liao, Lihui Chen. Emerging bimetallic metal-organic frameworks for photocatalytic carbon dioxide reduction. *Coordination Chemistry Reviews* 2026, 556 217704. <https://doi.org/10.1016/j.ccr.2026.217704>.
- [102] Wenqin Li, Jianmin Luo, Junli Feng, Yuhang Li, Bin Liu, Yi Zhang, Jun Zhao, Chuanyi Wang. Ingenious p-d orbital hybridization induced by atomic Yb doping for CO₂ reduction to CO. *Rare Metals* 2025, 44 (8) 5439-5451. <https://doi.org/10.1007/s12598-025-03307-w>.
- [103] Aathira M. Sadanandan, Jae-Hun Yang, Vidyasagar Devtade, Gurwinder Singh, Nithinraj Panangattu Dharmarajan, Mohammed Fawaz, Jang Mee Lee, Ehsan Tavakkoli, Chung-Hwan Jeon, Prashant Kumar, Ajayan Vinu. carbon nitride based nanoarchitectonics for nature-inspired photocatalytic CO₂ reduction. *Progress in Materials Science* 2024, 142 101242. <https://doi.org/10.1016/j.pmatsci.2024.101242>.
- [104] Chen Guan, Yulong Liao, Quanjun Xiang. Dual-facet engineering of surface carboxyl functionalization and interlayer potassium ions regulation in carbon nitride for enhanced CO₂ photoreduction. *Science China Materials* 2024, 67 (2) 473-483. <https://doi.org/10.1007/s40843-023-2703-0>.
- [105] Jinshan Chen, Jiangfeng Lu, Ran Lang, Chi Wang, Shuangyou Bao, Yuan Li, Kai Li, Maohong Fan. Enhanced and selective photocatalytic reduction of CO₂ to CH₄ using a Pt-loaded CuPc/g-C₃N₄ Z-scheme heterojunction catalyst. *Green Energy & Environment* 2025, 10 (6) 1348-1358. <https://doi.org/10.1016/j.gee.2025.01.006>.
- [106] I. Hsiang Tseng, Boju You, Poya Chang. Sugarcane bagasse supported graphitic carbon nitride for photocatalytic conversion of carbon dioxide. *Catalysis Communications* 2022, 164 106431. <https://doi.org/10.1016/j.catcom.2022.106431>.
- [107] Zeeshan Ajmal, Asif Hayat, Abdul Qadeer, Yu Zhao, Essam H. Ibrahim, Mahmood ul Haq, Kanwal Iqbal, Mohd Imran, Mohammed Kuku, Iftikhar Hussain, Hamid Ali, Yasin Orooji, John L. Zhou, Teng Ben. Advancements in MXene-based frameworks towards photocatalytic hydrogen production, carbon dioxide reduction and pollutant degradation: Current challenges and future prospects. *Coordination Chemistry Reviews* 2025, 523 216226. <https://doi.org/10.1016/j.ccr.2024.216226>.
- [108] Guangfu Liao, Yaqin Yu, Xin Liu, Peng Wang. Revealing the strain-induced spin polarization effect in MBene for efficient photocatalytic disinfection. *Environmental Chemistry and Safety* 2025, 1 (3) 9600044. <https://doi.org/10.26599/ECS.2025.9600044>.
- [109] Sheng Liu, Yanjun Zhang, Jun Du, Yuan Xue, Cheng Huang, Zushun Xu, Peng Wang, Zhengrong Wei, Zhanhui Yuan, Guangfu Liao, Qing Li. Facilitating carrier kinetics in dual S-Scheme heterojunctions through interface regulating strategy for H₂O₂ generation and nizatidine degradation. *Chemical Engineering Journal* 2025, 523 168949. <https://doi.org/10.1016/j.cej.2025.168949>.
- [110] Fungbili Basumatary, Angita Sarkar, Nituraj Mushahary, Bipul Das, Pankaj Saikia, Manickam Selvaraj, Sanjay Basumatary. Graphitic carbon nitride composites as advanced versatile materials for adsorption and photocatalytic degradation of emerging pollutants from wastewater. *Process Safety and Environmental Protection* 2024, 191 2416-2468. <https://doi.org/10.1016/j.psep.2024.09.077>.
- [111] Pengcheng Yan, Jing Huang, Guanyu Wu, Yu Zhang, Zhao Mo, Keqiang Xu, Min Ling, Sihua Dong, Li Xu, Henan Li. Construction of a In₂O₃/ultrathin g-C₃N₄ S-scheme heterojunction for sensitive photoelectrochemical aptasensing of diazinon. *Journal of Colloid and Interface Science* 2025, 679 653-661. <https://doi.org/10.1016/j.jcis.2024.10.016>.
- [112] Ying Dai, Wangui Peng, Yi Ji, Jia Wei, Junhao Che, Yongqiang Huang, Weihong Huang, Wenming Yang, Wanzhen Xu. A self-powered photoelectrochemical aptasensor using 3D-carbon nitride and carbon-based metal-organic frameworks for high-sensitivity detection of tetracycline in milk and water. *Journal of Food Science* 2024, 89 (11) 8022-8035. <https://doi.org/10.1111/1750-3841.17398>.
- [113] Yu Han, Lu Gan, Han Gong, Jiangang Han, Weichuan Qiao, Lijie Xu. Photoactivation of peroxydisulfate by wood pulp cellulose biochar/g-C₃N₄ composite for diclofenac degradation: the radical and nonradical pathways. *Biochar* 2022, 4 (1) 35. <https://doi.org/10.1007/s42773-022-00155-0>.
- [114] Liting Chen, Longqi Li, Yaqin Yu, Xinyu Luo, Yuanyuan Gao, Yipeng Chen, Yin Xiao, Shixiang Feng, Li Shuai, Guangfu Liao. Emerging metal-organic framework-based materials for photocatalytic nitrogen reduction reactions. *Materials Chemistry Frontiers* 2026, 10 (8) 1212-1241. <https://doi.org/10.1039/D6QM00109B>.
- [115] Diwakar Singh, Samad Razzaq, Ebrahim Tayyebi, Kai S. Exner. Selectivity control in the nitrogen reduction reaction over Mo₂C MXene by a nitrogen-rich environment. *ACS Catalysis* 2025, 15 (7) 5589-5600. <https://doi.org/10.1021/acscatal.4c04878>.
- [116] Yin Xiao, Ziheng Chen, Xin Liu, Xusheng Wang, Guixiang Ding,

- Zhaoqiang Wang, Peng Wang, Guangfu Liao. Perylene diimide-based photocatalysts: from molecular design to emerging applications. *Materials Horizons* 2025, 12 (23) 9922-9951. <https://doi.org/10.1039/D5MH01487E>.
- [117] Juan Wu, Shijun Nie, Hai Liu, Chunli Gong, Quanyuan Zhang, Zushun Xu, Guangfu Liao. Design and development of nucleobase modified sulfonated poly(ether ether ketone) membranes for high-performance direct methanol fuel cells. *Journal of Materials Chemistry A* 2022, <https://doi.org/10.1039/D2TA03166C>.
- [118] Amalia M. Grigoras, Federica Valentini, Loredana Latterini, Luigi Vaccaro. Heterogeneous iron-based catalysts for a sustainable photoinduced nitrogen fixation. *Green Energy & Environment* 2025, 10 (4) 733-755. <https://doi.org/10.1016/j.gee.2024.07.003>.
- [119] Lin Lei, Huiqing Fan, Yuxin Jia, Xiaobo Wu, Neng Hu, Qi Zhong, Weijia Wang. Surface-assisted synthesis of biomass carbon-decorated polymer carbon nitride for efficient visible light photocatalytic hydrogen evolution. *Journal of Colloid and Interface Science* 2023, 634 1014-1023. <https://doi.org/10.1016/j.jcis.2022.12.092>.
- [120] Yanyun Wang, Shuo Zhao, Yiwei Zhang, Wenxia Chen, Shenhao Yuan, Yuming Zhou, Ziwei Huang. Synthesis of graphitic carbon nitride with large specific surface area via copolymerizing with nucleobases for photocatalytic hydrogen generation. *Applied Surface Science* 2019, 463 1-8. <https://doi.org/10.1016/j.apsusc.2018.08.215>.
- [121] Asif Hayat, Muhammad Sohail, Mohamed S. Hamdy, Sunil Kumar Baburao Mane, Mohammed A. Amin, Amir Zada, T. A. Taha, Mohammed Muzibur Rahman, Arkom Palamanit, D. I. Medina, Javid Khan, W. I. Nawawi. Biomass Lignin Integrated Polymeric carbon nitride for Boosted photocatalytic Hydrogen and Oxygen Evolution Reactions. *Molecular Catalysis* 2022, 518 112064. <https://doi.org/10.1016/j.mcat.2021.112064>.
- [122] Zhengdong Xu, Xun Su, Penghui Yang, Junbo Zhong, Minjiao Li, Clemens Burda, Lin Dou. efficient photocatalytic CO₂ and Cr(VI) reduction on carbon quantum dots/carbon nitride heterojunctions. *Fuel* 2025, 381 133285. <https://doi.org/10.1016/j.fuel.2024.133285>.
- [123] Ting Niu, Yulu Mao, Yujing Lv, Mengjie Li, Yongchun Liu, Peng Yang, Quan Gu. Amyloid-like protein-modified carbon nitride as a bioinspired material for enhanced photocatalytic CO₂ reduction. *ACS Applied Materials & Interfaces* 2024, 16 (46) 63495-63508. <https://doi.org/10.1021/acsami.4c12315>.
- [124] Zhouze Chen, Loic Jiresse Nguetsa Kuate, Hefan Zhang, Jianhua Hou, Huabing Wen, Changyu Lu, Chunsheng Li, Weilong Shi. Photothermally enabled black g-C₃N₄ hydrogel with integrated solar-driven evaporation and photo-degradation for efficient water purification. *Separation and Purification Technology* 2025, 355 129751. <https://doi.org/10.1016/j.seppur.2024.129751>.
- [125] Piti Charurungsipong, Bhumin Than-ardna, Hathaikam Manuspiya. A novel polydopamine-coated bacterial cellulose/g-C₃N₄ membrane for highly efficient photocatalytic degradation of methylene blue. *International Journal of Biological Macromolecules* 2024, 283 137738. <https://doi.org/10.1016/j.ijbiomac.2024.137738>.
- [126] Ermelinda Falletta, Mariangela Longhi, Alessandro Di Michele, Daria C. Boffito, Claudia L. Bianchi. Floatable graphitic carbon nitride/alginate beads for the photodegradation of organic pollutants under solar light irradiation. *Journal of Cleaner production* 2022, 371 133641. <https://doi.org/10.1016/j.jclepro.2022.133641>.
- [127] Sijie Zhou, Chunhua Zhang, Liangjun Xia, Zhuan Fu, Na Zhu, Junyao Gong, Xiaofeng Wang, Pei Lyu, Li Li, Weilin Xu. A flexible and weavable lignocellulose-based photocatalyst supported by natural three-dimensional porous juncus effusus for highly efficient degradation of environmental contaminants. *ACS Applied Materials & Interfaces* 2022, 14 (24) 27955-27967. <https://doi.org/10.1021/acsami.2c06207>.
- [128] Liangpang Xu, Yang Liu, Lejing Li, Zhuofeng Hu, Jimmy C. Yu. Fabrication of a photocatalyst with biomass waste for H₂O₂ synthesis. *ACS Catalysis* 2021, 11 (23) 14480-14488. <https://doi.org/10.1021/acscatal.1c03690>.
- [129] Peijie Ma, Xu Zhang, Cong Wang, Zhiwei Wang, Kaiwen Wang, Yibo Feng, Jiaxing Wang, Yadi Zhai, Jiguang Deng, Lihua Wang, Kun Zheng. Band alignment of homojunction by anchoring CN quantum dots on g-C₃N₄ (0D/2D) enhance photocatalytic hydrogen peroxide evolution. *Applied Catalysis B: Environmental* 2022, 300 120736. <https://doi.org/10.1016/j.apcatb.2021.120736>.
- [130] Yinglong Lu, Xin Yue, Junjie Cai, Xi He, Lejing Li, Quan Zhou, Chengyu Duan, Ruilin Wang, Mengdi Sun, Zheshun Ou, Huimin Liu, Guanghui Luo, Xiaoli Wang, Jimmy C. Yu, Zhuofeng Hu. Synthesis of high-efficiency phosphatized catalysts by using organophosphorus and biomass for photocatalytic hydrogen peroxide production via oxygen reduction. *Applied Catalysis B: Environment and Energy* 2024, 347 123771. <https://doi.org/10.1016/j.apcatb.2024.123771>.
- [131] Nuo Chen, Jingjing Xia, Longfei Li, Qianru Lv, Kun Zhao, Munir Ahmad, Zhourong Xiao, Shuaijie Wang, Fei Ye, Qingrui Zhang. Comprehensive enhancement of photocatalytic H₂O₂ generation and antibacterial efficacy on carbon nitride through a straightforward polydopamine coating strategy. *Surfaces and Interfaces* 2025, 56 105566. <https://doi.org/10.1016/j.surf.2024.105566>.
- [132] Ton That Buu, Nguyen Duy Hai, Che Quang Cong, Nguyen Thanh Hoai Nam, Ta Dang Khoa, Dang Gia Vy, Nguyen Thao Nguyen, Doan Thi Yen Oanh, Nguyen Huu Hieu. A case study of different bismuth oxyhalides BiOX (X = F, Cl, Br, and I)/biochar-derived rice husk@graphitic carbon nitride for the robustness of H₂O₂ photoproduction and antibiotic photodegradation. *Journal of Water Process Engineering* 2024, 57 104558. <https://doi.org/10.1016/j.jwpe.2023.104558>.

- [133] Kavitha S, Yukesh Kannah Ravi, Ginni G, Lise Appels, Mieczysław Łapkowski, Yogendra Kumar Mishra, Palanivelu Kandasamy, Palanichamy Rajaguru, Pugalanthi Velan, Rajesh Banu Jeyakumar. Recent advances in photocatalytic conversion of lignocellulosic biomass: routes, limitations, and outlook. *ACS Engineering Au* 2025, 5 (3) 191-225. <https://doi.org/10.1021/acsengineingau.4c00059>.
- [134] Qiaozhi Zhang, Zhonghao Wan, Iris K. M. Yu, Daniel C. W. Tsang. Sustainable production of high-value gluconic acid and glucaric acid through oxidation of biomass-derived glucose: A critical review. *Journal of Cleaner production* 2021, 312 127745. <https://doi.org/10.1016/j.jclepro.2021.127745>.
- [135] Peng Zhang, Zhen Shen, Lixia Jia, Jieshan Qiu. Biomass-derived carbon for boosting photocatalysis. *Small* 2026, 22 (8) e12210. <https://doi.org/10.1002/sml.202512210>.
- [136] Saishuai Bai, Meiqing Yang, Jizhou Jiang, Xiaomiao He, Jing Zou, Zhiguo Xiong, Guodong Liao, Song Liu. Recent advances of MXenes as electrocatalysts for hydrogen evolution reaction. *npj 2D Materials and Applications* 2021, 5 (1) 78. <https://doi.org/10.1038/s41699-021-00259-4>.
- [137] Jiamei Wang, Qin Qin, Fangyi Li, Yulianti Anjarsari, Wei Sun, Rifda Azzahidah, Jing Zou, Kun Xiang, Huijuan Ma, Jizhou Jiang, Arramel. Recent advances of MXenes Mo₂C-based materials for efficient photocatalytic hydrogen evolution reaction. *carbon Letters* 2023, 33 (5) 1381-1394. <https://doi.org/10.1007/s42823-022-00401-2>.
- [138] Jiamei Wang, Jizhou Jiang, Fangyi Li, Jing Zou, Kun Xiang, Haitao Wang, Youji Li, Xin Li. Emerging carbon-based quantum dots for sustainable photocatalysis. *Green Chemistry* 2023, 25 (1) 32-58. <https://doi.org/10.1039/d2gc03160d>.
- [139] Riki Subagyo, Azis Yudhowijoyo, Novia Amalia Sholeha, Sutrisno Salomo Hutagalung, Didik Prasetyoko, Muhammad Danang Birowosuto, Arramel Arramel, Jizhou Jiang, Yuly Kusumawati. Recent advances of modification effect in Co₃O₄-based catalyst towards highly efficient photocatalysis. *Journal of Colloid and Interface Science* 2023, 650 1550-1590. <https://doi.org/10.1016/j.jcis.2023.07.117>.
- [140] Jing Zou, Jing Wu, Yizhou Wang, Fengxia Deng, Jizhou Jiang, Yizhou Zhang, Song Liu, Neng Li, Han Zhang, Jiaguo Yu, Tianyou Zhai, Husam N. Alshareef. Additive-mediated intercalation and surface modification of MXenes. *Chemical Society Reviews* 2022, 51 (8) 2972-2990. <https://doi.org/10.1039/d0cs01487g>.