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Graphitic carbon nitride (g-C_3N_4) as an emerging photocatalyst for sustainable environmental applications: a comprehensive review

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Graphitic carbon nitride (g-C_3N_4) stands as a prominent and sustainable photocatalyst, offering a transformative solution to pressing environmental and energy challenges. This review article provides a comprehensive examination of g-C_3N_4, spanning its synthesis methods, structural properties, photocatalytic mechanisms, and diverse applications. By delving into various synthesis techniques and their respective merits, we reveal recent breakthroughs that underscore the material's growing significance. Unveiling the critical structural attributes governing photocatalytic performance, including bandgap, surface area, and porosity, we explore the impact of doping and modification on enhancing its capabilities. In elucidating the photocatalytic mechanisms, we showcase how g-C_3N_4 facilitates crucial processes like water splitting, pollutant degradation, and solar-driven carbon dioxide reduction, emphasizing its unique selectivity and efficiency. Through concrete examples and case studies, we highlight its versatility in applications ranging from water purification to hydrogen production and air quality enhancement, underscoring the environmental and economic benefits that come with its adoption. Challenges such as quantum efficiency and charge carrier recombination are addressed, alongside a forward-looking perspective on emerging trends and innovations. Ultimately, this review positions g-C_3N_4 as a sustainable game-changer in the realm of environmental and energy technologies, offering a promising path towards a more sustainable future.

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Sustainability spotlight

Graphitic carbon nitride (g-C_3N_4) is emerging as a promising catalyst in the realm of sustainable environmental applications. Its unique properties, including efficient light absorption and electron–hole pair generation, make it a key player in addressing pressing environmental challenges. By utilizing g-C_3N_4 as a photocatalyst, we are taking a significant step towards a greener and cleaner future. This sustainable innovation paves the way for eco-friendly solutions in wastewater treatment, air purification, and renewable energy production, marking a brighter path towards a more sustainable planet.

1. Introduction

In an era characterized by escalating environmental challenges and the unrelenting pursuit of sustainable solutions, photocatalysis has emerged as a transformative technology with the potential to revolutionize our approach to pressing global issues.[1–3] The ability to harness sunlight and convert it into a powerful driving force for a myriad of chemical reactions holds the promise of addressing some of the most urgent concerns facing society today.[4–7] Among the plethora of photocatalytic materials, graphitic carbon nitride (g-C_3N_4) has risen to prominence, captivating the imagination of researchers and practitioners alike. Its unique combination of properties, including excellent stability, ease of synthesis, and a suitable bandgap, positions it as an ideal candidate for sustainable applications, ranging from water purification and renewable energy production to air quality improvement and carbon management.[8–12]

The imperative for sustainable solutions in the face of mounting environmental challenges is undeniable. Water scarcity, pollution, and the depletion of fossil fuels have compelled humanity to explore novel technologies that mitigate these issues while minimizing environmental harm.[13–16] Photocatalysis, as an eco-friendly and energy-efficient process, has emerged as a ray of hope.[17,18] By exploiting semiconductor materials that can absorb solar radiation and catalyze chemical reactions, photocatalysis has the potential to transform pollutants into harmless byproducts, produce clean energy from sunlight, and address the daunting issue of global warming through carbon capture and utilization.[19–22]

The utilization of graphitic carbon nitride (g-C_3N_4) as a photocatalyst has garnered substantial attention within the

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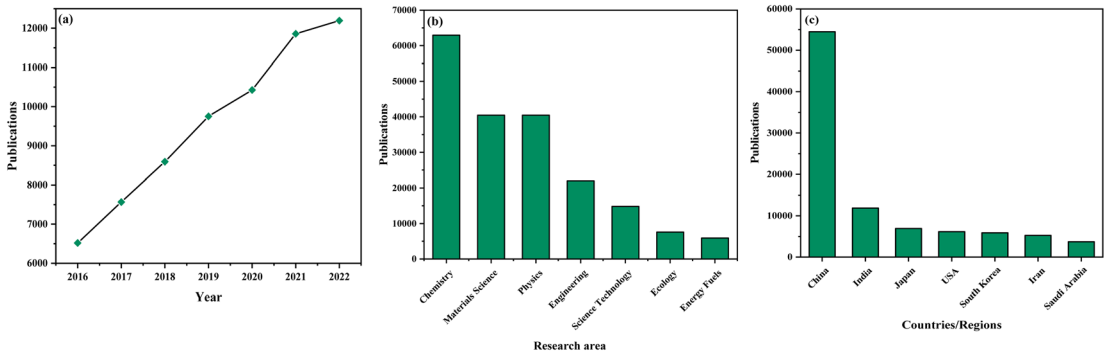


Fig. 1 Exploring the landscape of graphitic carbon nitride (g-C_3N_4) as a photocatalyst: (a) number of publications in the past years, (b) distribution of the publications across scientific fields, and (c) worldwide distribution of publications (source: Web of Science).

scientific community, where a concerted effort is being made to decipher the distinctive qualities that render these catalysts truly exceptional. A thorough examination of literature resources accessible through prominent databases unveils a notable surge in publications pertaining to the application of graphitic carbon nitride (g-C_3N_4) as a photocatalyst in recent times, indicative of a remarkable growth trajectory (as illustrated in Fig. 1(a)). This escalating trend emphatically underscores the escalating significance of graphitic carbon nitride (g-C_3N_4) as a photocatalyst in the context of addressing intricate chemical transformations, sustainability-related challenges, and the formulation of environmentally friendly and more efficacious processes. Researchers are increasingly captivated by the extensive potential and the diverse array of applications offered by graphitic carbon nitride (g-C_3N_4) as a photocatalyst, thereby reflecting the field's profound importance in shaping the future landscape of chemistry and sustainable technologies.[23–28]

Research in this field spans a broad spectrum of prominent scientific disciplines, with a central focus on areas including chemistry, materials science, physics, engineering, science technology, ecology, and energy fuels (as depicted in Fig. 1(b)). These research endeavors predominantly revolve around foundational and fundamental inquiries, representing a fundamental exploration into the core principles and mechanisms that govern the functionality of graphitic carbon nitride (g-C_3N_4) as a photocatalyst. This interdisciplinary approach emphasizes the wide-ranging and profound implications associated with graphitic carbon nitride (g-C_3N_4) as a photocatalyst, as it extends its influence into diverse scientific domains, ultimately accentuating its pivotal role in advancing our comprehension of chemical processes, sustainability practices, and the evolution of innovative technologies.[29–34]

The global landscape of publications in this field presents an intriguing picture, as depicted in Fig. 1(c). Notably, China emerges as the epicenter of active research on graphitic carbon nitride (g-C_3N_4) as a photocatalyst, underlining the nation's significant contributions to the advancements in this particular domain. Following closely are India, Japan, and a host of other nations, all actively engaged in research pursuits pertaining to graphitic carbon nitride (g-C_3N_4) as a photocatalyst. This worldwide distribution underscores the widespread acknowledgment of the paramount importance of graphitic carbon nitride (g-C_3N_4) as a photocatalyst across diverse regions on a global scale. Furthermore, it mirrors the collaborative and international character intrinsic to scientific research, with researchers hailing from various nations collectively striving to expand the frontiers of knowledge and devise sustainable solutions in the realm of photocatalysis.

While various photocatalysts have demonstrated promising capabilities, the distinctive properties of g-C_3N_4 have thrust it into the limelight. Its structure, comprised of carbon and nitrogen atoms arranged in a two-dimensional conjugated framework, not only imparts exceptional chemical stability but also affords a favorable electronic band structure, making it well-suited for photochemical applications.[35–38] The synthesis of g-C_3N_4 has been refined through diverse methods, offering researchers the flexibility to tailor its properties for specific applications. These methods encompass thermal polymerization, chemical vapor deposition, and solvothermal processes, among others, each with its own advantages and limitations.[39–45]

Intriguingly, g-C_3N_4's remarkable photocatalytic performance extends beyond the realm of traditional semiconductor photocatalysts. Its capacity to generate electron–hole pairs upon exposure to light, facilitate charge separation, and participate in redox reactions has opened up new avenues for sustainable applications.[46–48] Whether it be the degradation of organic pollutants in water, the production of clean hydrogen fuel *via* water splitting, the removal of noxious gases from the atmosphere, or the conversion of carbon dioxide into value-added chemicals, g-C_3N_4's versatility and efficiency have illuminated the path toward a more sustainable future.[27,49–53]

This comprehensive review endeavors to shed light on the multifaceted attributes of g-C_3N_4 as a photocatalyst, exploring its synthesis techniques, structural properties, photocatalytic mechanisms, and diverse applications. It is our aspiration that by delving into the intricacies of g-C_3N_4 photocatalysis, we can provide a roadmap for academic and industrial researchers to harness the immense potential of this material in advancing sustainability, catalyzing environmental stewardship, and paving the way for a cleaner, greener, and more sustainable world.

2. Synthesis methods

The synthesis of graphitic carbon nitride (g-C_3N_4) has undergone significant development over the years, offering researchers a versatile toolkit to tailor its properties for specific photocatalytic applications. The following sections explore several key synthesis methods, each with its own advantages and limitations.

2.1 Thermal polymerization

One of the most widely employed methods for g-C_3N_4 synthesis is thermal polymerization of low-cost precursors, such as melamine, urea, cyanamide, dicyanamide, thiourea, cyanuric acid *etc.* This process typically involves the heating of these precursors at moderate temperatures (around 500–600 °C) under inert gas atmospheres (Fig. 2). The thermal polymerization route generates a layered g-C_3N_4 structure with a high surface area, making it suitable for various photocatalytic applications. The method's simplicity and cost-effectiveness have contributed to its popularity.[54–56]

2.2 Chemical vapor deposition (CVD)

CVD represents an alternative approach to g-C_3N_4 synthesis, offering precise control over the material's thickness and morphology. In CVD, volatile precursors, such as cyanamide, are introduced into a high-temperature reactor, where they decompose and deposit as g-C_3N_4 on substrates (shown in Fig. 3). This method allows for the growth of thin films and nanostructures, enabling applications in photovoltaics and optoelectronics. However, CVD may require more specialized equipment and is often associated with higher production costs.[57–60]

2.3 Solvothermal and hydrothermal methods

Solvothermal and hydrothermal routes involve the reaction of precursors in high-pressure, high-temperature aqueous or organic solvents (Fig. 4). These methods offer control over the morphology and structure of g-C_3N_4 by adjusting reaction conditions. Solvent selection plays a crucial role in influencing the final product's properties. Hydrothermal synthesis is particularly effective in producing hierarchical g-C_3N_4

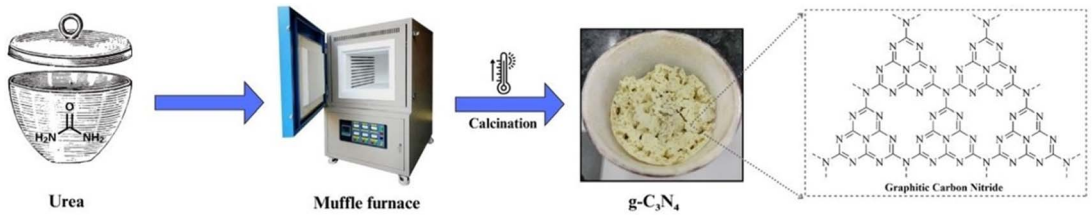


Fig. 2 Synthesis of g-C_3N_4 *via* thermal polymerization method.

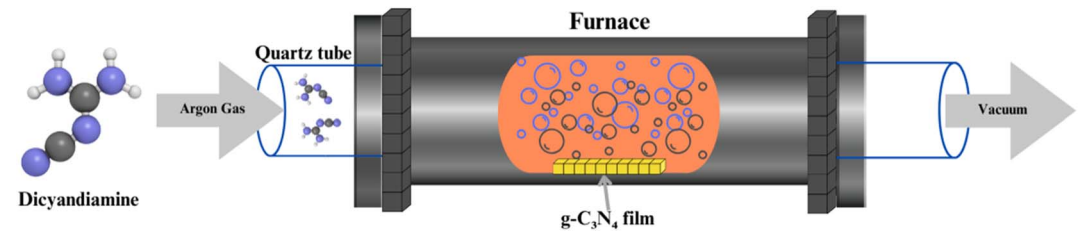


Fig. 3 Synthesis of g-C_3N_4 *via* CVD method.

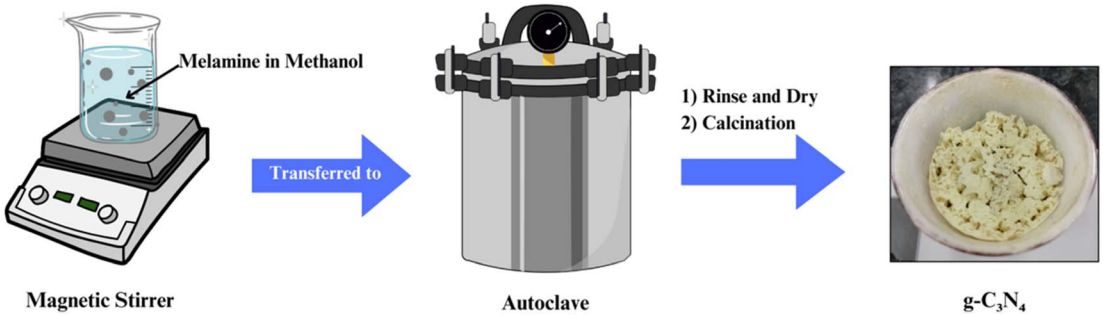


Fig. 4 Hydrothermal synthesis of g-C_3N_4 particles.

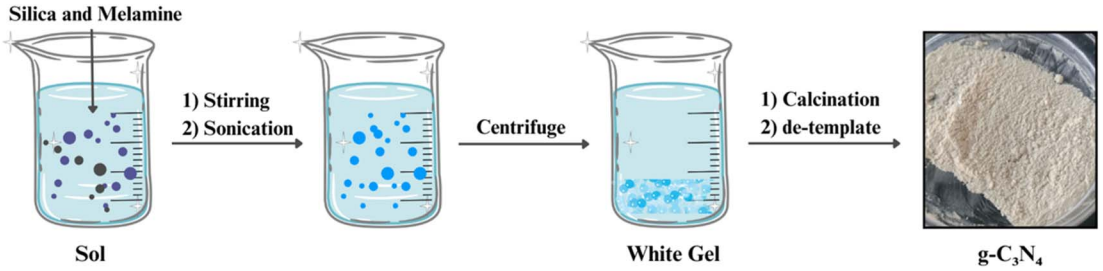


Fig. 5 Template-assisted synthesis of g-C_3N_4 particles.

structures with enhanced photocatalytic activity. These methods are advantageous for tailoring g-C_3N_4 for specific applications and have gained prominence in recent years.[61–65]

2.4 Template-assisted synthesis

Template-assisted synthesis involves the use of templates, such as mesoporous silica or carbonaceous materials, to guide the formation of g-C_3N_4 with specific structures (Fig. 5). By using templates with desired pore sizes and shapes, researchers can control the surface area and porosity of g-C_3N_4, which are critical factors affecting its photocatalytic performance. This approach enables the creation of g-C_3N_4 materials with finely tuned properties for applications like pollutant removal and solar energy conversion.[66–70]

2.5 Doping and co-doping strategies

To further enhance the photocatalytic activity of g-C_3N_4, doping and co-doping with other elements, such as sulfur, boron, and metals, have been explored (as shown in Fig. 6). Doping introduces impurities into the g-C_3N_4 lattice, modifying its electronic structure and creating additional active sites for photocatalytic reactions. Co-doping involves the simultaneous incorporation of two or more elements to achieve synergistic effects. These strategies play a pivotal role in improving g-C_3N_4's efficiency and selectivity in various photocatalytic processes.[71–75]

The synthesis of graphitic carbon nitride (g-C_3N_4) has advanced significantly, providing a diverse set of methods with distinct advantages and limitations. Thermal polymerization, involving low-cost precursors like melamine, offers simplicity and cost-effectiveness, resulting in a layered g-C_3N_4 structure suitable for various applications. Chemical vapor deposition (CVD) allows precise control over thickness and morphology but may entail higher production costs and specialized equipment. Solvothermal and hydrothermal methods, utilizing high-pressure and high-temperature conditions, provide morphology control and have gained popularity for tailoring g-C_3N_4 properties. Template-assisted synthesis uses templates to guide specific structures, influencing surface area and porosity critical for photocatalytic performance. Doping and co-doping strategies enhance photocatalytic activity by modifying the electronic structure.

Comparing these methods reveals trade-offs in terms of cost, complexity, and yield. Thermal polymerization is cost-effective and straightforward but might lack precision. CVD offers control but at higher costs. Solvothermal and hydrothermal methods provide control over morphology but involve specialized conditions. Template-assisted synthesis allows tailored structures but might be more intricate. Doping strategies enhance performance but add complexity. The choice depends on desired properties and applications, influencing cost-effectiveness and efficiency.[24]

In summary, the choice of synthesis methods for g-C_3N_4 is influenced by the desired properties and intended applications. Researchers and engineers can select from these diverse synthesis techniques to tailor g-C_3N_4 materials that meet the specific demands of sustainable environmental applications, from water purification to renewable energy production.

3. Structural properties

Graphitic carbon nitride (g-C_3N_4) exhibits a unique two-dimensional structure composed of carbon and nitrogen atoms, which imparts distinctive structural properties crucial

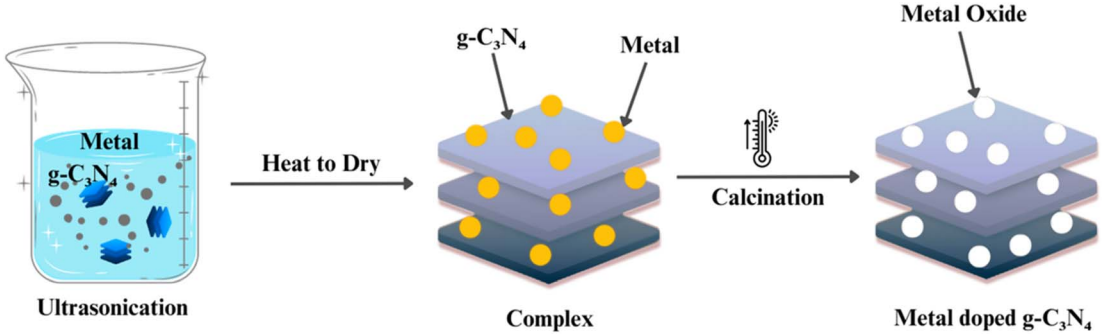


Fig. 6 Metal/metal oxide doped g-C_3N_4 synthesis *via* doping strategies.

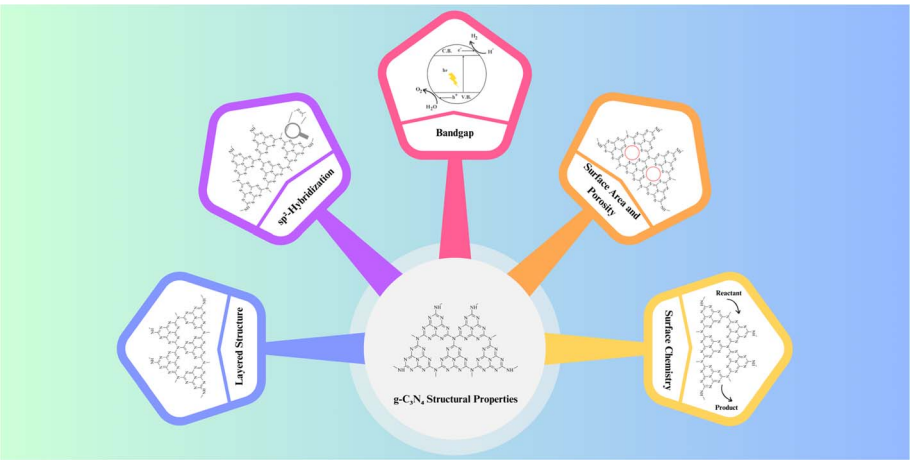


Fig. 7 Structural properties of pristine g-C_3N_4.

for its photocatalytic performance.[76] Understanding these properties is essential for tailoring g-C_3N_4 materials to specific applications and optimizing their efficiency. The key structural attributes are provided in Fig. 7.

3.1 Layered structure

At its core, g-C_3N_4 consists of stacked layers of carbon and nitrogen atoms arranged in a planar, hexagonal lattice. This layered structure resembles that of graphite, giving rise to its name, "graphitic". Each layer is composed of tri-*s*-triazine (C_3N_3) units, and the layers are held together by weak van der Waals forces. This layered configuration provides a large surface area for potential reactant adsorption and photocatalytic reactions, making g-C_3N_4 an attractive material for various applications.[36]

3.2 sp^2-hybridization

The carbon atoms within the g-C_3N_4 lattice adopt sp^2-hybridization, resulting in trigonal planar geometry. This sp^2-hybridized carbon configuration is responsible for the formation of delocalized π-bonds, contributing to the material's excellent electrical conductivity and optical properties. This electron-rich network facilitates charge carrier mobility and separation, which are essential for efficient photocatalysis.[34]

3.3 Bandgap

The electronic band structure of g-C_3N_4 plays a pivotal role in its photocatalytic activity. It exhibits a moderate bandgap typically around 2.7 to 2.8 eV, making it responsive to visible light. Photons with energy equal to or greater than the bandgap can excite electrons from the valence band to the conduction band, initiating the photocatalytic process. The bandgap value allows g-C_3N_4 to harness a substantial portion of the solar spectrum, rendering it effective for solar-driven applications.[31]

3.4 Surface area and porosity

The layer-by-layer structure of g-C_3N_4 results in a high surface area, providing ample sites for reactant adsorption and subsequent photocatalytic reactions. The interlayer spacing between g-C_3N_4 layers can be tuned to create mesopores and micropores, further enhancing its surface area and porosity. These structural features facilitate efficient mass transport and reactant accessibility, promoting photocatalytic efficiency.[7]

3.5 Surface chemistry

The surface of g-C_3N_4 can be modified through functionalization, which introduces various functional groups such as amino, hydroxyl, and carboxyl groups. These modifications can influence the material's surface charge, hydrophilicity, and chemical reactivity, thus tailoring its suitability for specific photocatalytic applications. Surface functionalization also enables the attachment of co-catalysts, enhancing charge separation and overall photocatalytic performance.[31]

Moving to structural properties, g-C_3N_4's layered structure, sp^2-hybridization, moderate bandgap, high surface area, and porosity are key features. The layered structure provides a large surface area for reactions, while sp^2-hybridization contributes to electrical conductivity. The moderate bandgap (2.7–2.8 eV) enables responsiveness to visible light, crucial for solar-driven applications. High surface area and porosity, achieved through the layer-by-layer structure and tuned interlayer spacing, facilitate efficient mass transport and reactant accessibility. Surface chemistry, modified through functionalization, further tailors properties for specific applications.[24] Understanding these structural properties allows researchers to design and engineer g-C_3N_4 materials with optimized characteristics for diverse photocatalytic applications. By tailoring the layer spacing, bandgap, and surface chemistry, g-C_3N_4 can be fine-tuned to address specific environmental and energy challenges, contributing to a sustainable and cleaner future.

4. Photocatalytic mechanism

The remarkable photocatalytic activity of graphitic carbon nitride (g-C_3N_4) stems from its unique structural and electronic properties, which enable it to initiate and accelerate photochemical reactions under illumination. Understanding the underlying photocatalytic mechanisms is pivotal for harnessing

the full potential of g-C_3N_4 in sustainable environmental and energy applications. The primary steps involved in the photocatalytic mechanism of g-C_3N_4 are depicted in Scheme 1.[77–79]

The modification of g-C_3N_4 is important for photocatalytic applications. The interface formed can reduce the recombination of photoinduced charge and improve the absorptivity of visible light. Meanwhile, the high redox ability of electrons and holes is maintained. Therefore, design and synthesis of different types of g-C_3N_4-based heterojunction photocatalysts has important research value for achieving efficient photodegradation of pollutants and improving the increasingly serious environmental pollution. In recent years, photocatalysts for type II-heterojunctions, g-C_3N_4-based p–n heterojunctions and Z-scheme heterojunctions have been developed rapidly and have shown great potential advantages in various photocatalytic systems. By constructing different types of heterostructures, the photocatalytic performance of g-C_3N_4 has been greatly improved.[80]

4.1 Light absorption and electron–hole generation

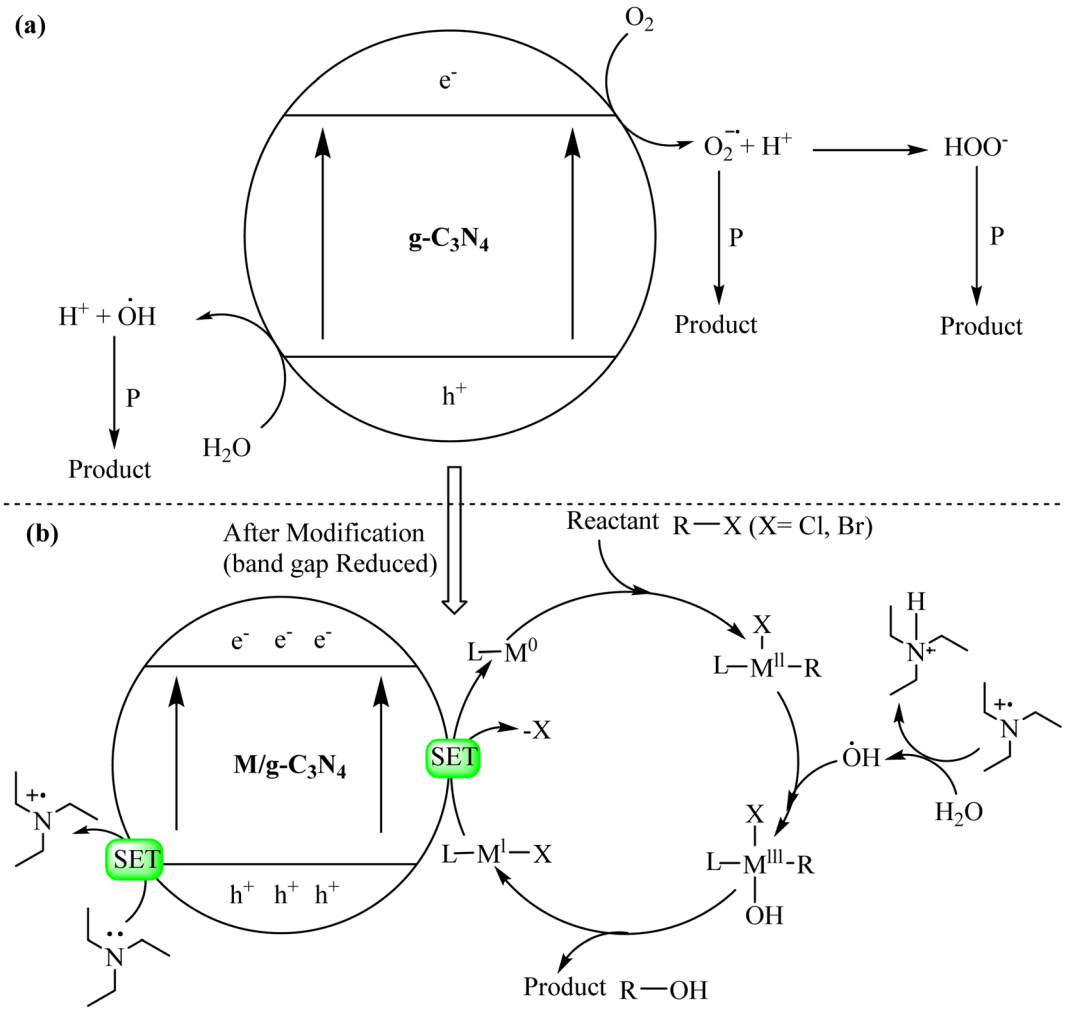
When g-C_3N_4 is exposed to photons with energy equal to or greater than its bandgap (typically around 2.7 to 2.8 eV), electrons in the valence band are excited to the conduction band, creating electron–hole pairs. This initial step is the foundation of photocatalysis, as it generates highly reactive species that can drive subsequent reactions.

4.2 Charge separation

Once electron–hole pairs are generated, the electrons and holes become mobile within the g-C_3N_4 lattice. Efficient charge separation is crucial to prevent recombination of electrons and holes, which would diminish photocatalytic efficiency. The unique layered structure of g-C_3N_4, with its sp^2-hybridized carbon atoms, facilitates rapid charge separation, allowing electrons to move freely through the lattice.

4.3 Redox reactions

The separated electrons and holes are poised to participate in redox reactions on the g-C_3N_4 surface. Electrons in the conduction band are capable of reducing various species, while the holes in the valence band can oxidize substances. For instance, in the context of water purification, electrons can reduce water molecules to form hydroxyl radicals (˙OH), which are highly reactive and effective at degrading organic pollutants.



Scheme 1 General mechanisms of (a) g-C_3N_4 catalyzed reactions and (b) metal/g-C_3N_4-catalyzed visible light driven reactions.

4.4 Reaction with adsorbates

Adsorption of target molecules or pollutants onto the g-C_3N_4 surface is a critical prerequisite for their degradation. The large surface area and active sites provided by g-C_3N_4 facilitate the adsorption of organic molecules, pollutants, or gases. Once adsorbed, these species can directly interact with the photogenerated electrons or holes, initiating degradation or transformation reactions.

4.5 Oxygen activation (for oxygen-dependent reactions)

In reactions involving oxygen, g-C_3N_4 can also activate molecular oxygen (O_2) to form reactive oxygen species (ROS) like superoxide radicals ($^{\bullet}O^{2-}$) and singlet oxygen ($^1O_2$). These ROS further enhance the photocatalytic activity by participating in oxidation reactions and promoting the breakdown of organic pollutants.

4.6 Surface states and co-catalysts

Surface states on g-C_3N_4, as well as co-catalysts like metal nanoparticles or semiconductors, can further enhance charge separation and facilitate specific reaction pathways. Co-catalysts, for example, can serve as electron sinks or sources, improving overall photocatalytic performance.

The specific photocatalytic mechanisms can vary depending on the target reaction and the environment in which g-C_3N_4 is employed. Whether it's water splitting, pollutant degradation, or carbon dioxide reduction, g-C_3N_4's ability to generate and effectively utilize electron–hole pairs makes it a versatile and efficient photocatalyst for a wide range of sustainable applications. By elucidating these fundamental photocatalytic mechanisms, researchers can design and optimize g-C_3N_4-based photocatalysts to achieve higher efficiency, selectivity, and stability, ultimately contributing to the advancement of sustainable technologies and environmental preservation.[81–83]

5. Applications

Graphitic carbon nitride (g-C_3N_4) has emerged as a versatile and eco-friendly photocatalyst with a remarkable ability to address pressing environmental and energy challenges. Its wide range of applications spans various domains, each contributing to the advancement of sustainability. Here, we delve into the diverse and transformative applications of g-C_3N_4, elucidating its role in:

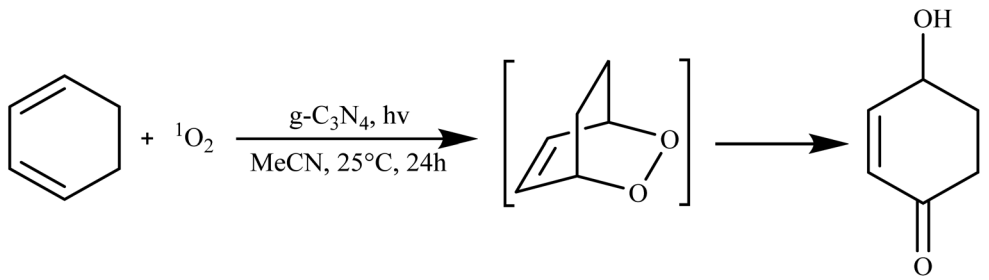
5.1 Various organic transformations

g-C_3N_4 has showcased its prowess in catalyzing various organic transformations, including the synthesis of organic chemicals, pharmaceuticals, and fine chemicals. Its unique surface chemistry and catalytic activity enable selective reactions, reducing the need for harsh reaction conditions and hazardous reagents. For instance, g-C_3N_4 has been employed in the synthesis of diverse organic compounds, such as benzene derivatives, imines, and quinolines, showcasing its potential in green and sustainable chemistry.[84]

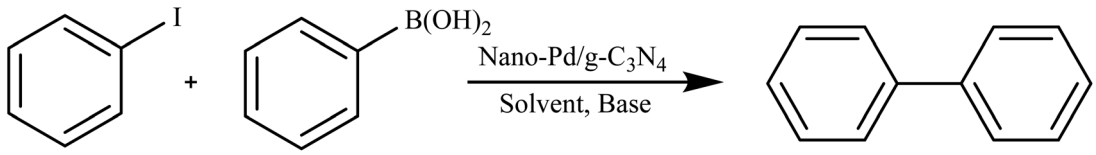
In their study, Quadrelli *et al.* found that when g-C_3N_4 is oxidized, it exhibits excellent catalytic capabilities for generating singlet oxygen ($^1O_2$) under photochemical conditions. This particular form of graphitic carbon nitride, produced through the bulk and hard template pyrolysis of melamine, is considered a highly promising material for fostering environmentally-friendly chemical reactions. The oxidized g-C_3N_4 catalyst, referred to as catalyst, demonstrated a range of performance levels, from satisfactory to outstanding, in the Diels–Alder cycloaddition reaction with *in situ* generated $^1O_2$, particularly in the case of 1,3-cyclohexadiene and with alkenes during ene reactions. Additionally, it displayed notable oxidative capabilities when interacting with aromatic olefins, as illustrated in Scheme 2.[85]

Sarkar *et al.* conducted a study on the utilization of a nano-Pd/gC_3N_4 composite as a catalyst for the microwave-assisted Suzuki cross-coupling of various aryl halides with different arylboronic acids. The reactions took place in an aqueous medium under aerobic conditions. The catalyst proved to be exceptionally efficient, with impressive turnover frequencies (TOFs) of approximately 12 000 per hour across a range of substituted reactants. This work exemplifies an innovative and environmentally friendly approach to catalysis, combining the advantages of reusability, water as a solvent, and microwave irradiation as an alternative heating method, as depicted in Scheme 3.[86]

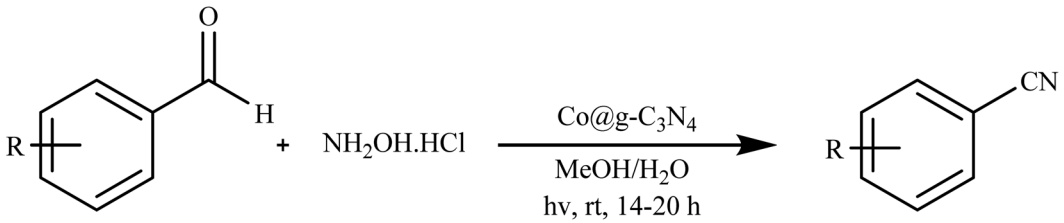
Rai *et al.* introduced an innovative and environmentally friendly process using visible light to efficiently convert aldehydes into nitriles. This method employs Co@g-C_3N_4 as a photocatalyst in an aqueous environment, operating under normal ambient conditions, as illustrated in Scheme 4. Key attributes of



Scheme 2 Diels–Alder cycloaddition reaction *via* oxidized g-C_3N_4 catalyst.



Scheme 3 Suzuki cross-coupling of various aryl halides *via* nano-Pd/gC_3N_4 composite.



Scheme 4 Co@g-C_3N_4 photocatalyst for conversion of aldehydes into nitriles.

this designed photocatalyst include its selectivity, stability, and reusability across multiple reactions. Its heterogeneous nature, combined with its effectiveness under ambient conditions, makes it a highly advantageous alternative for potential application in various industries.[87]

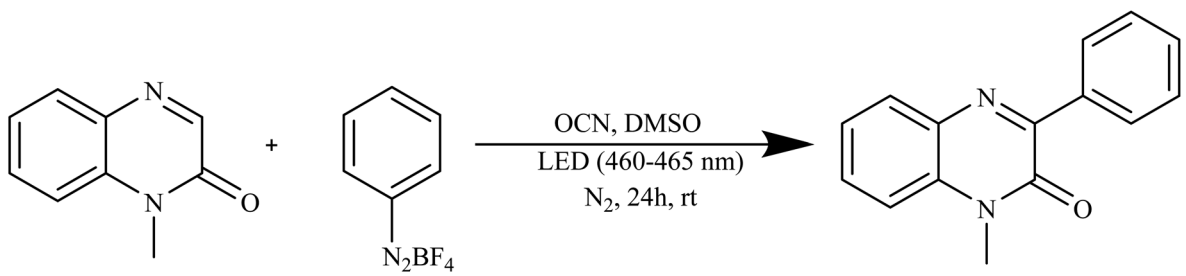
Yao and colleagues introduced an inventive technique for producing oxygen-doped carbon nitride material (OCN) through a hydrothermal–calcination method. The OCN material exhibited outstanding performance as a stable photocatalyst, displaying excellent efficiency and recyclability. This catalyst facilitated the creation of 3-arylquinoxalin-2(1*H*)-ones by catalytically breaking down aryl diazonium salts under blue light exposure, all accomplished without the utilization of metals or external additives, as illustrated in Scheme 5. This approach not only provides a novel, environmentally friendly, and easily recyclable pathway but also signifies a sustainable synthetic strategy for generating these valuable structural entities.[88]

The case study illustrates various catalytic systems (Table 1) such as oxidized g-C_3N_4, nano-Pd/g-C_3N_4 composites, Co@g-C_3N_4, and oxygen-doped graphitic carbon nitride (OCN) which displayed remarkable performance in diverse organic transformation reactions. These innovative catalysts showcase assorted strengths, including high efficiency, recyclability, and environmental friendliness, providing a promising array of options for sustainable and eco-friendly chemical synthesis across various industries.

In the realm of organic transformations, g-C_3N_4 emerges as a formidable ally, ushering in a new era of sustainable chemistry. Its ability to facilitate selective reactions under mild conditions reduces the environmental footprint of chemical synthesis. From the creation of valuable pharmaceutical intermediates to the sustainable production of fine chemicals, g-C_3N_4 showcases its versatility and eco-friendliness. As the world seeks greener and more sustainable pathways in the realm of chemical synthesis, g-C_3N_4 stands as a beacon of hope, embodying the promise of harnessing solar-driven catalysis to meet the demands of a rapidly changing world, where sustainability and efficiency are paramount.

5.2 Hydrogen production through water splitting

The efficient utilization of solar energy to split water into hydrogen and oxygen holds the key to clean and renewable hydrogen production. g-C_3N_4's bandgap aligns well with the solar spectrum, allowing it to harness sunlight for photocatalytic water splitting. By absorbing photons and generating electron–hole pairs, g-C_3N_4 initiates the water splitting reaction, producing clean hydrogen fuel, a promising step toward a hydrogen-based economy.



Scheme 5 Oxygen doped carbon nitride used as a catalyst for the synthesis of 3-arylquinoxalin-2(1*H*)-ones.

Table 1 g-C_3N_4-based catalysts for various organic transformations

Entry	Catalyst	Organic transformation	Yield (%)	Ref.
1	g-C_3N_4	Diels–Alder reaction	55%	84
2	Pd@g-C_3N_4	Suzuki–Miyaura cross-coupling	99%	85
3	Co@g-C_3N_4	Nitrile synthesis	92%	86
4	Oxygen-doped g-C_3N_4	Synthesis of 3-arylquinoxalin-2(1*H*)-ones	68%	87

Han *et al.* created g-C_3N_4 composites with silver (Ag) using two methods: precipitation–calcination (DeCNexAg) and annealing (ZeCNexAg). These Ag-based composites exhibited enhanced photocatalytic activity under visible light. The best hydrogen production was achieved with DeCNexAg containing 5% Ag_2CO_3, producing 4.6 times more hydrogen than ZeCNe5% Ag. This enhanced performance was attributed to the presence of metallic Ag and additional active sites on the DeCNe5% Ag surface, aiding in charge separation and transfer. The study also highlighted the role of the local surface plasmon resonance (LSPR) effect and the close interaction between Ag and g-C_3N_4 in improving hydrogen production through water splitting as shown in Fig. 8.[89]

Samaniego-Benitez *et al.* created a g-C_3N_4/NiS hybrid photocatalyst through a combination of thermal decomposition and hydrothermal techniques. This hybrid material exhibited a remarkable hydrogen production yield of 1230 mmol H_2/h, which was significantly higher than that achieved by g-C_3N_4 and TiO_2 photocatalysts. The kinetic constant for this hybrid material was measured at 307.1 h^{-1}. This enhanced photocatalytic activity can be attributed to the reduced rate of electron–hole recombination, which results from the mixed phases found in the hybrid structure of the photocatalyst, as depicted in Fig. 9(a).[90]

Li *et al.* used g-C_3N_4 and Ag/AgBr NPs as the carrier and co-catalyst to create g-C_3N_4/Ag/AgBr heterojunctions through solvothermal technology. They analyzed the samples' characteristics and studied their hydrogen evolution catalytic activity through water splitting. The catalyst exhibited the best performance with low overvoltage, a shallow Tafel slope, and high catalytic activity, even without a Pt co-catalyst. This heterojunction photocatalyst demonstrated excellent photostability and recyclability. The addition of Ag/AgBr NPs to two-dimensional g-C_3N_4 nanosheets enhanced their photoresponse and photocatalytic activity as depicted in Fig. 9(b).[91]

Zhu and co-authors devised a distinctive Mn_3O_4/g-C_3N_4 p–n heterojunction through an *in situ* growth method. This heterojunction notably enhances the light absorption capacity of g-C_3N_4. The resulting photocatalyst exhibits remarkable efficiency in the hydrogen evolution reaction (HER), achieving a rate of approximately 2700 μmol g^{-1} h^{-1} for wavelengths beyond 420 nm and maintaining stability over 15 hours of continuous H_2 production. The Mn_3O_4/g-C_3N_4 system also displays elevated external quantum efficiencies (EQEs) at various wavelengths. Additionally, it adeptly catalyzes both H_2 and O_2 evolution under simulated sunlight and accomplishes overall water splitting to generate H_2 and O_2 products in a stoichiometric molar ratio of 2 : 1. This research introduces a straightforward method for crafting high-performance g-C_3N_4-based heterostructure materials for efficient photocatalytic overall water splitting, as depicted in Fig. 10.[92]

The case study highlights diverse approaches to enhancing photocatalytic hydrogen production using g-C_3N_4 composites (Table 2). While Han *et al.*'s Ag-based composites leverage

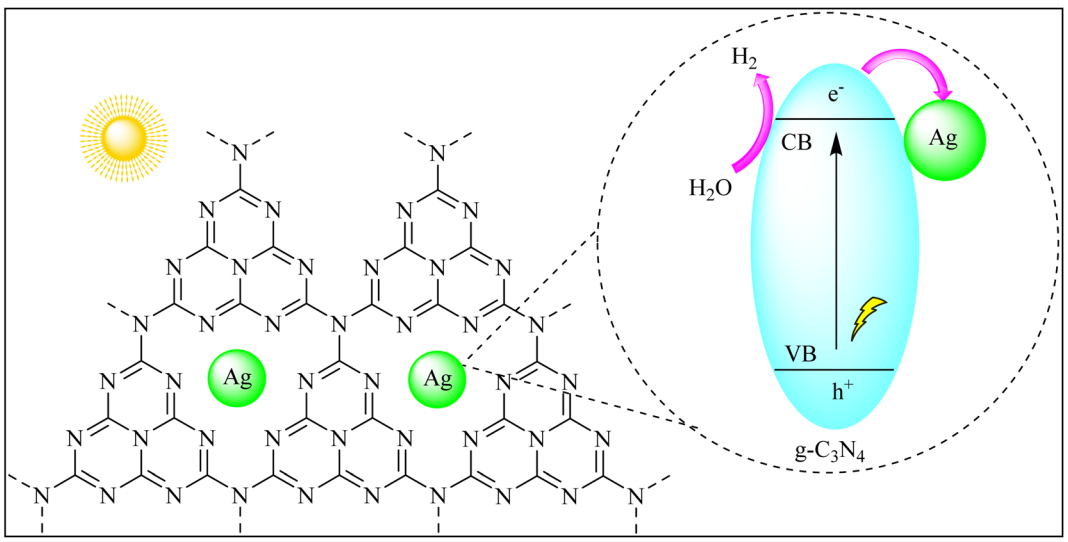


Fig. 8 Photocatalytic hydrogen production with Ag/g-C_3N_4 composites under visible light.

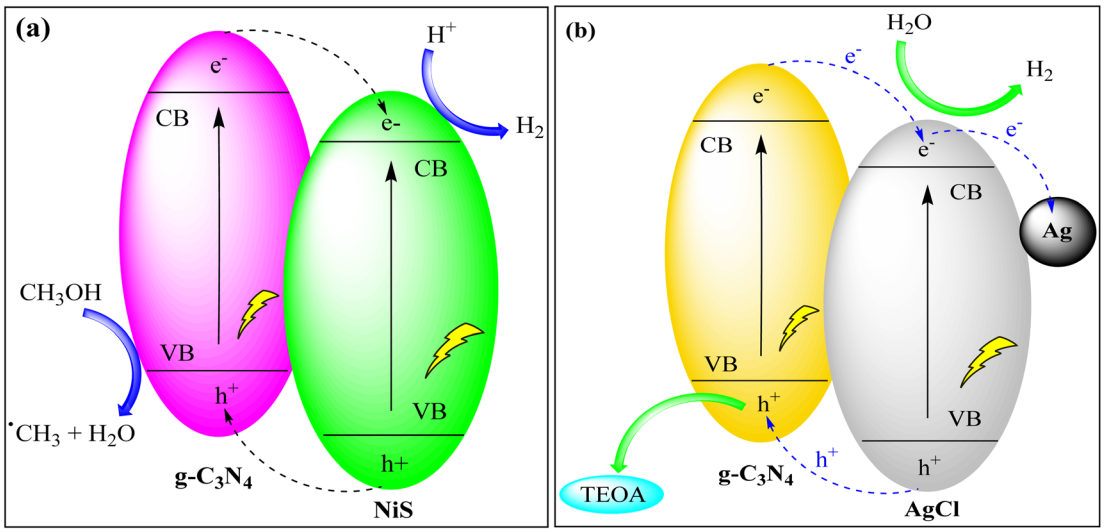


Fig. 9 (a) Hydrogen production *via* g-C_3N_4/NiS photocatalyst under UV light irradiation and (b) photocatalytic hydrogen production *via* the Ag@g-C_3N_4/AgCl heterostructure.

metallic Ag and active sites for improved charge separation, Samaniego-Benitez *et al.*'s g-C_3N_4/NiS hybrid focuses on minimizing electron–hole recombination through mixed phases. Li *et al.*'s g-C_3N_4/Ag/AgBr heterojunction demonstrates the effectiveness of incorporating co-catalysts for superior catalytic activity and stability, while Zhu *et al.*'s Mn_3O_4/g-C_3N_4 p–n heterojunction introduces a unique strategy with high efficiency and overall water splitting capabilities under simulated sunlight. These studies collectively underscore the versatility and innovation in tailoring g-C_3N_4-based photocatalysts for enhanced hydrogen evolution.

In the quest for clean and renewable energy sources, g-C_3N_4 emerges as a key player in the vital endeavor of hydrogen production through water splitting. Its unique ability to harvest solar energy and catalyze the conversion of water into hydrogen represents a sustainable solution with far-reaching

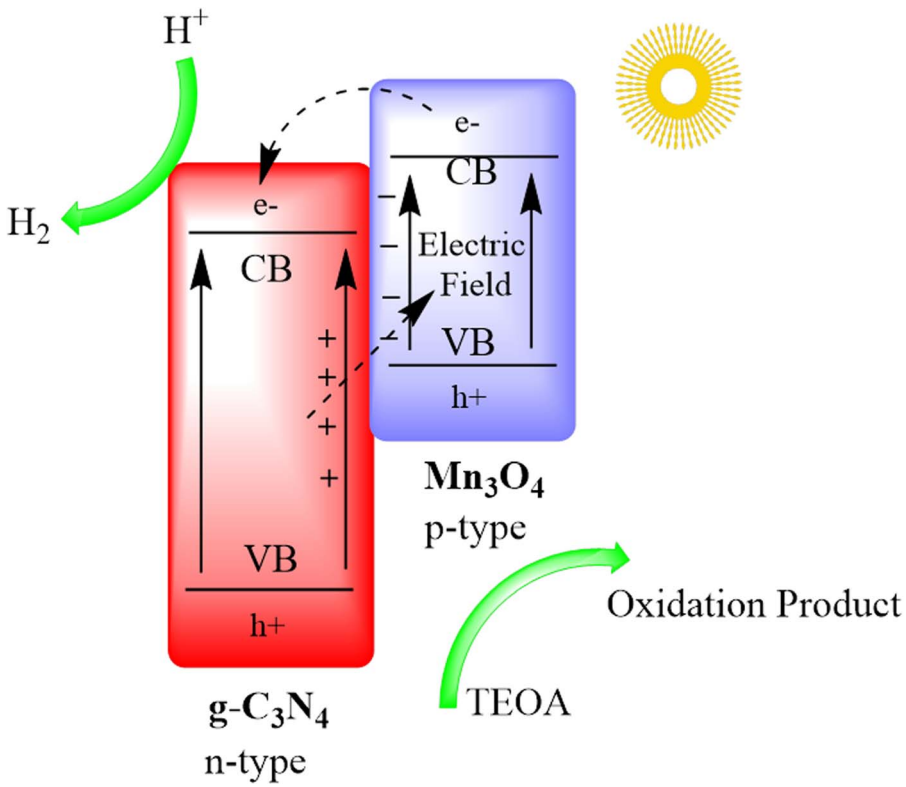


Fig. 10 Mn_3O_4/g-C_3N_4 based p–n heterojunction for hydrogen production.

Table 2 Photocatalytic hydrogen production *via* g-C_3N_4 based catalysts

Entry	Catalyst	Conditions	H_2 productivity/ μmol g^{-1} h^{-1}	Reference material H_2 productivity/μmol g^{-1} h^{-1}	Enhancement relative to conventional g-C_3N_4	Ref.
1	Ag/g-C_3N_4	300 W Xe lamp (λ > 420 nm)	153.33	33.49	4.6	89
2	NiS/g-C_3N_4	UV pen ray Hg lamp (254 nm, 4.4 mW cm^{-2})	307.5	277.5	1.10	90
3	g-C_3N_4-Ag/AgBr	300 W Xe lamp	47.84	NA	NA	91
4	Mn_3O_4/g-C_3N_4	300 W Xe lamp (λ > 420 nm)	2700	NA	NA	92

implications. As we look toward a future fueled by clean energy, g-C_3N_4 offers a promising pathway, contributing not only to the mitigation of climate change but also to the establishment of a hydrogen-based economy. With the absorption of each photon and splitting of each water molecule, g-C_3N_4 takes us one step closer to a world powered by abundant, eco-friendly hydrogen fuel, ushering in a new era of energy sustainability.

5.3 Water purification and treatment

One of the most critical applications of g-C_3N_4 is in water purification and treatment. Its photocatalytic prowess enables the degradation of organic pollutants and the removal of toxic heavy metals from contaminated water sources. Specific examples include the degradation of dyes, pharmaceuticals, and pesticides, as well as the removal of heavy metals like chromium and lead. By providing a sustainable and efficient means of water remediation, g-C_3N_4 contributes to safer and cleaner water resources.[93]

Ding *et al.* successfully synthesized a nanocomposite of magnetic graphene oxide (mGO) and graphitic carbon nitride (g-C_3N_4), denoted as mGCN, for the photoreduction of U(VI) in wastewater using visible LED light irradiation. mGCN exhibited high photocatalytic activity, reusability, and selectivity for U(VI) reduction. The photoreduction process achieved a remarkable U(VI) extraction capacity of 2880.6 mg g^{-1}. Mechanistic studies revealed that U(VI) was converted to metastudtite during the photoreduction process. This research contributes to the advancement of photocatalytic methods for addressing uranium wastewater treatment, as illustrated in Fig. 11.[94]

Gnana Prakash *et al.* developed g-C_3N_4 and g-C_3N_4/ZnO nanocomposite photocatalysts for crystal violet degradation using melamine pyrolysis and hydrothermal methods. The nanocomposite showed superior photocatalytic efficiency (97%) compared to pristine ZnO and g-C_3N_4, with a 1.4 times higher rate constant. It exhibited excellent stability through multiple recycling tests. Hole (h^+) species were found to be the primary drivers of crystal violet degradation. The enhanced performance of the g-C_3N_4/ZnO nanocomposite is attributed to improved visible light absorption and the formation of a heterojunction between g-C_3N_4 and ZnO, promoting efficient charge carrier separation, as depicted in Fig. 12.[95]

Kumar and colleagues synthesized graphitic carbon nitride (g-C_3N_4) by reducing melamine using a pyrolysis method. They then improved its characteristics to produce porous g-C_3N_4 (p-g-C_3N_4) through chemical protonation. The photocatalytic performances of both materials were assessed by decomposing organic dyes under sunlight. The protonation process induced a blue-shift in the optical absorption edge of g-C_3N_4. The study demonstrated that g-C_3N_4 exhibited superior photocatalytic efficiency compared to its pristine counterpart. p-g-C_3N_4 showed significantly enhanced degradation efficiency for various dyes under sunlight, attributed to an increased surface area that exposed more active sites for dye degradation, as depicted in Fig. 13.[96]

Comparing the three studies (Table 3), Ding *et al.*'s mGCN nanocomposite stands out for its effective photoreduction of U(VI) in wastewater, showcasing high activity, reusability, and selectivity with a remarkable extraction capacity. Gnana Prakash *et al.*'s g-C_3N_4/ZnO nanocomposite demonstrates superior photocatalytic efficiency in crystal violet degradation, attributed to enhanced visible light absorption and efficient charge carrier separation in the heterojunction structure. Kumar *et al.*'s work

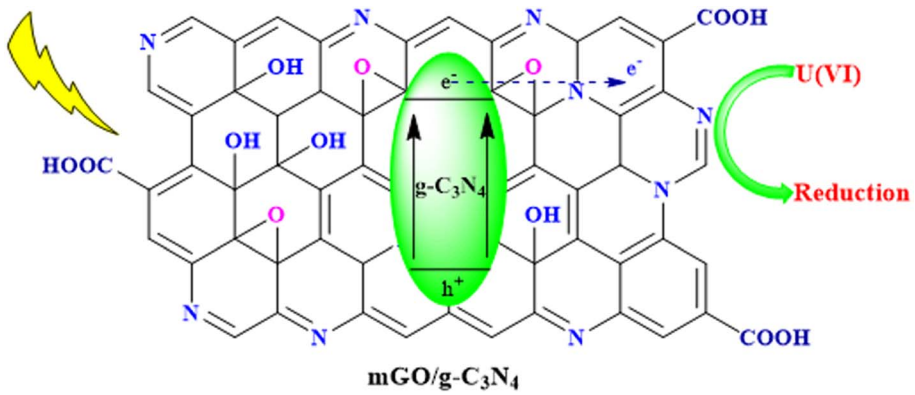


Fig. 11 Photocatalytic reduction of U(VI) in wastewater using the mGO/g-C_3N_4 nanocomposite under visible LED light irradiation.

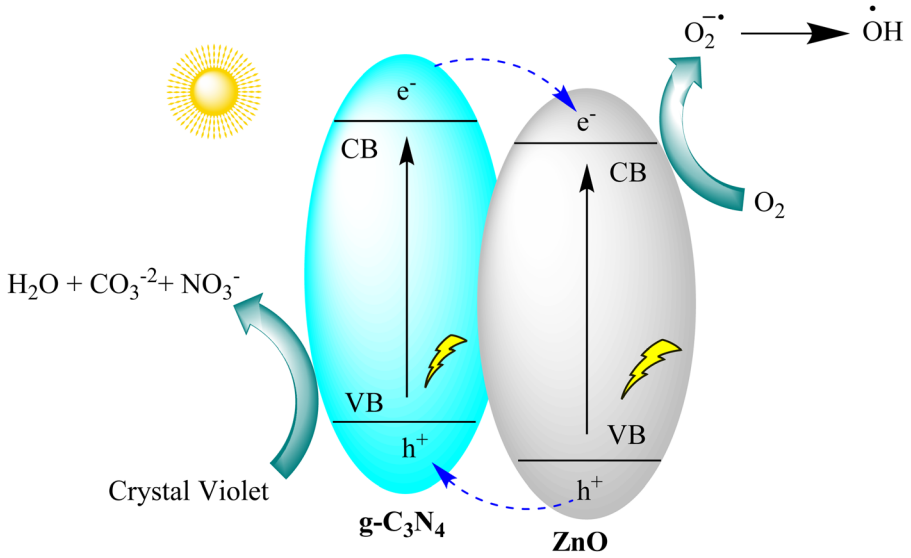


Fig. 12 g-C_3N_4/ZnO heterostructure for organic dye degradation under visible light irradiation.

focuses on porous g-C_3N_4, highlighting its superior photocatalytic efficiency for dye degradation under sunlight due to increased surface area and exposure of active sites. These studies collectively underscore the versatility of g-C_3N_4-based photocatalysts for diverse applications in environmental remediation.

In the realm of water purification and treatment, g-C_3N_4 stands as a beacon of hope, offering a sustainable and efficient solution to the pressing challenges of water pollution. Its ability to harness the power of sunlight to degrade organic pollutants and remove toxic heavy metals from contaminated water sources represents a transformative approach to safeguarding one of our most precious resources. As we confront the ever-growing concerns of water quality and scarcity, g-C_3N_4 paves the way for cleaner and safer water supplies. With each photocatalytic reaction, it exemplifies the potential for science and innovation to address the critical issue of water pollution, ensuring that future generations will inherit a world with access to clean and potable water. In the intersection of environmental stewardship and technological advancement, g-C_3N_4's role in water purification and treatment is not merely a solution; it is a promise of a more sustainable and water-secure future.

5.4 Air purification and pollutant removal

The degradation of volatile organic compounds (VOCs) and the removal of noxious gases from the atmosphere are essential for improving air quality. g-C_3N_4's photocatalytic activity extends to air purification applications, where it effectively degrades VOCs

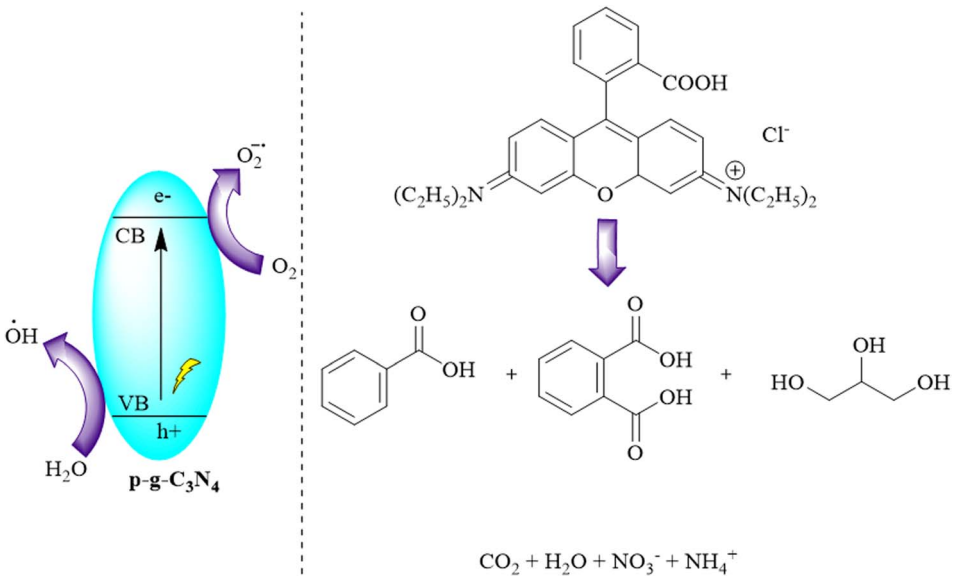


Fig. 13 Porous g-C_3N_4 for photocatalytic dye degradation.

Table 3 Pollutant degradation *via* g-C_3N_4 based catalysts

Entry	Catalyst	Organic dye	Conditions	Removal efficiency (%)	Reference material efficiency (%)	Ref.
1	mGO/g-C_3N_4	NA	5 mg catalyst, methanol, 30 mL 20 mg L^{-1} U(VI) solution, 8 W LED lamp	96	NA	94
2	g-C_3N_4/ZnO	Crystal violet	25 mg of catalyst and 25 mL of 20 ppm crystal violet solution, solar irradiation	97	88	95
3	p-g-C_3N_4	Crystal violet Methylene blue Rhodamine-B	25 mg catalyst, 25 mL (20 mg L^{-1}) of an aqueous solution, sunlight irradiation	98 99 93	92 83 32	96

like formaldehyde, toluene, and xylene. Additionally, it can facilitate the conversion of harmful gases like nitrogen oxides (NO_x) into less harmful compounds. The utilization of g-C_3N_4 in air purification technologies helps combat air pollution and promote healthier living environments.

Zhou and their team successfully incorporated SnO_2 quantum dots into graphitic carbon nitride (g-C_3N_4) *via* a simple synthesis method. This led to the development of photocatalysts that generated minimal NO_2 and achieved a 32% NO removal rate when exposed to visible light for 30 minutes. The attachment of SnO_2 quantum dots not only improved the photocatalysts' ability to reduce NO_2 but also enhanced the transfer of photogenerated carriers, improving NO removal. This study provided an accessible way to combine a wide bandgap semiconductor (SnO_2) with strong photo-oxidation capabilities and layered g-C_3N_4, which responds well to visible light for NO removal. Future research is needed to eliminate NO_2 byproducts in the photocatalytic NO removal process, as shown in Fig. 14.[97]

Huang *et al.* created a g-C_3N_4/TiO_2 composite coating for removing NO_x in ambient air. They applied it directly to roads using TiO_2 hydrosol, eliminating the need for dispersants or binders. The coating had strong adhesion, easy regeneration, and light-induced superhydrophilicity, making it suitable for long-term use. It achieved daily NO and NO_x reductions of 59.0% and 27.8%, respectively, and higher rates during morning and afternoon hours with weak sunlight. This was due to the coating's broad visible light absorption, critical for pollution reduction. Outdoor results showed that NO_x removal depended on solar irradiation and pollutant concentration, with the latter being more important due to reaction kinetics. In conclusion, the g-C_3N_4/TiO_2 composite and spraying method offer a simple and effective way to create photocatalytic pavement for air purification as shown in Fig. 15.[98,99]

You and collaborators synthesized MgO@g-C_3N_4 heterojunctions through a one-step pyrolysis process involving commercial MgO and urea, leading to a significant enhancement in photocatalytic efficiency. The 3% MgO@g-C_3N_4 sample exhibited the highest efficiency in NO photodegradation at 75.4%. However, beyond 3% MgO, the efficiency experienced a decline. The heterojunction structure, resulting from the combination of MgO and g-C_3N_4, played a crucial role in improving appearance quantum efficiency and prolonging electron recombination, ultimately contributing to superior NO photodegradation. The composite also demonstrated favorable conversion of NO to NO_2 and other by-products. Notably, the 3%

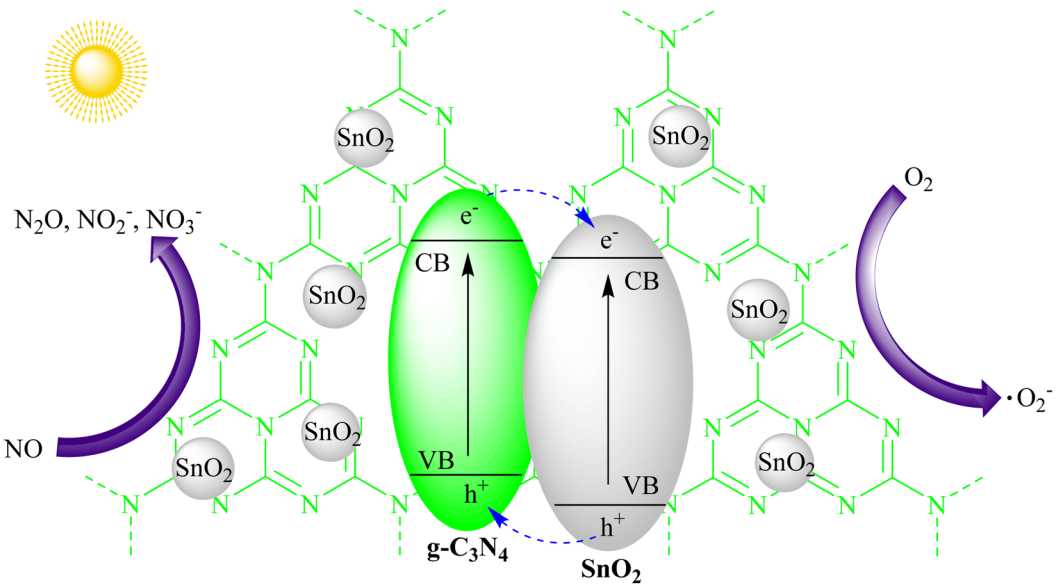


Fig. 14 g-C_3N_4/SnO_2 heterostructure for removal of NO under visible light irradiation.

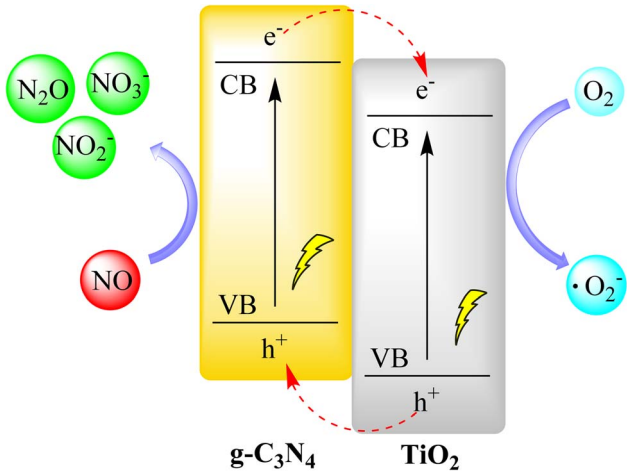


Fig. 15 g-C_3N_4/TiO_2 heterostructure for removal of NO under visible light irradiation.

MgO@g-C_3N_4 maintained high reusability after five cycles, with only a modest 7.1% decrease in efficiency. Characterization techniques confirmed the presence of MgO and its impact on optical properties, suggesting scalability for future applications. Overall, the study provides valuable insights into optimizing MgO@g-C_3N_4 photocatalysis, as illustrated in Fig. 16.[100]

Comparing the three studies (Table 4), Zhou *et al.*'s incorporation of SnO_2 quantum dots into g-C_3N_4 showcases a simple method for developing photocatalysts with a 32% NO removal rate under visible light. This approach effectively combines the strong photo-oxidation capabilities of SnO_2 with the layered structure of g-C_3N_4, demonstrating potential for NO reduction. Huang *et al.*'s g-C_3N_4/TiO_2 composite coating directly applied to roads offers a practical and efficient solution for NO_x removal from ambient air, achieving daily reductions and demonstrating adaptability to varying sunlight conditions. You and collaborators' synthesis of MgO@g-C_3N_4 heterojunctions provides valuable insights into optimizing photocatalysis for NO degradation, emphasizing the importance of the composite structure for enhanced efficiency and reusability. These studies collectively contribute to the development of effective and accessible photocatalytic methods for NO and NO_x removal in different environmental contexts.

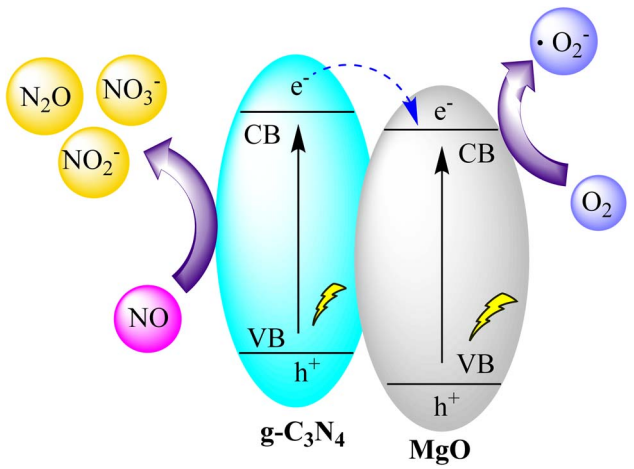


Fig. 16 MgO@g-C_3N_4 for degradation of NO under visible light irradiation.

In the realm of air purification and the removal of noxious pollutants, g-C_3N_4 emerges as a powerful agent of change, working tirelessly to enhance the quality of the air we breathe. Its remarkable photocatalytic abilities, adept at degrading volatile organic compounds (VOCs) and transforming harmful gases, have the potential to combat air pollution and improve the health of our environments. As the world grapples with the consequences of urbanization and industrialization, g-C_3N_4 offers a glimmer of hope for cleaner and healthier air. With each chemical bond broken and each pollutant neutralized, it embodies the promise of harnessing sustainable technologies to restore the purity of our atmosphere. In the ongoing battle against air pollution, g-C_3N_4's role is not merely that of a catalyst; it is a symbol of our collective commitment to cleaner, more breathable air, ensuring a future where all can thrive in an environment free from harmful pollutants.

5.5 Solar-driven carbon dioxide reduction

Addressing the challenge of increasing carbon dioxide (CO_2) levels in the atmosphere necessitates innovative approaches for its conversion into valuable products. g-C_3N_4 has demonstrated promise in the solar-driven reduction of CO_2 into hydrocarbons and other valuable chemicals. This application holds immense potential for both mitigating climate change and producing sustainable feedstocks for various industries.

Li *et al.* created a versatile Pt/In_2O_3/g-C_3N_4 catalyst using precise assembly techniques. This catalyst efficiently produced formic acid (HCOOH) during visible-light-driven CO_2 reduction by synergistically promoting hydrogen generation, CO_2 activation, and minimizing electron–hole recombination. It also had a long operational life due to stability and prevented Pt leaching. This work offers a promising method to design multifunctional catalysts for high-yield, room-temperature, and normal-pressure photocatalytic CO_2 reduction as depicted in Fig. 17.[101]

Khan *et al.* used a CuO/g-C_3N_4 photocatalyst to produce methanol *via* photoelectrochemical reduction of CO_2. The CuO/g-C_3N_4 photocathode outperformed others, showing a tenfold increase in the photocurrent response. It had high incident photon-to-current efficiency and significantly increased methanol production. The photocathode also had improved faradaic and quantum efficiency compared to other configurations. The study discussed the CO_2-to-methanol conversion mechanism in detail, as shown in Fig. 18.[102]

Yu *et al.* successfully created a Z-scheme binary composite photocatalytic system by combining g-C_3N_4 and ZnO through a simple calcination process, using affordable precursors, urea, and zinc nitrate hexahydrate. This composite exhibited improved light absorption in the visible spectrum compared to pure g-C_3N_4, thanks to the introduction of defect states within the g-C_3N_4 due to the interference of ZnO crystallization.

Table 4 Air pollutant degradation *via* g-C_3N_4-based catalytic systems

Entry	Catalyst	Conditions	NO removal efficiency (%)	Reference material efficiency (%)	Ref.
1	SnO_2 quantum dots on g-C_3N_4	0.4 g catalyst, NO concentration 600 ppb, 150 W tungsten halogen lamp (λ > 420 nm)	32	19	97
2	g-C_3N_4/TiO_2	5 L Teflon air bag (232-05, Tedlar®) for 45 min with a height of 1.0–1.5 m from the ground by using a sampling pump with a flow rate of 0.1 L min^{-1}	38.9	23.5 (TiO_2)	98
3	MgO@g-C_3N_4	0.2 g catalyst, NO concentration 500 ppb, 10 mL water, 80 °C, 300 W xenon lamp	75.4	62.8	100

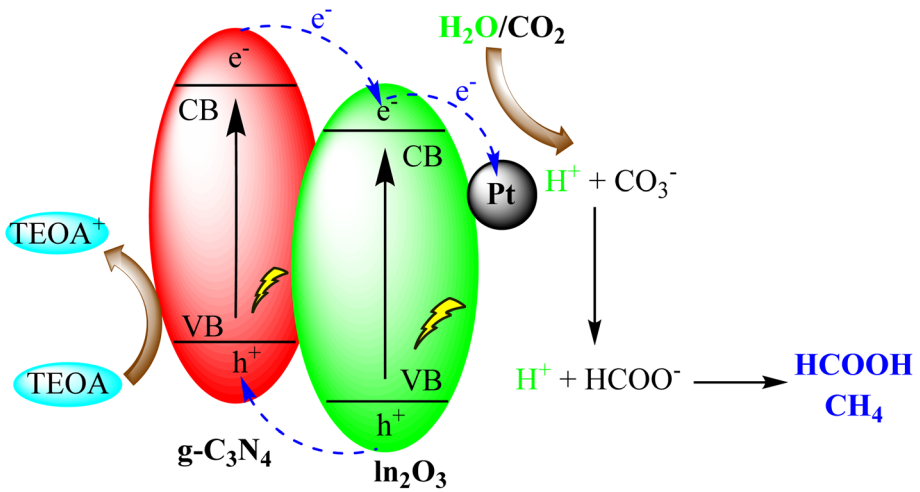


Fig. 17 Pt/In_2O_3/g-C_3N_4 heterostructure for CO_2 reduction under visible light irradiation.

Notably, the g-C_3N_4/ZnO photocatalyst displayed a 2.3-fold increase in its ability to catalyze the conversion of CO_2 into CH_3OH while maintaining selectivity, as shown in Fig. 19. This indicates the promising potential of this composite for efficient CO_2 reduction applications.[103]

Pant and co-authors presented a straightforward approach for crafting a conjugated organic–inorganic hybrid photocatalyst (TiO_2/g-C_3N_4) through sol–gel synthesis followed by conventional pyrolysis. The heterostructure formed by TiO_2 and g-C_3N_4 efficiently facilitated the separation of electrons and holes, as evidenced by their respective band edge positions. This TiO_2 and g-C_3N_4 heterostructure exhibited a type II heterojunction, renowned for promoting enhanced charge separation and mitigating charge recombination. The augmented charge separation contributed to an increased photoreduction of CO_2, yielding valuable methanol as the photo-reduced product. The composite catalysts demonstrated a higher methanol yield (31.7 μmol g^{-1}) compared to the individual components. The study underscores the crucial role of charge separation in a straightforward heterostructure catalyst, leading to heightened product formation through CO_2 reduction under a visible light source, as depicted in Fig. 20.[104]

Li *et al.*'s versatile Pt/In_2O_3/g-C_3N_4 catalyst stands out for its ability to efficiently produce formic acid during visible-light-

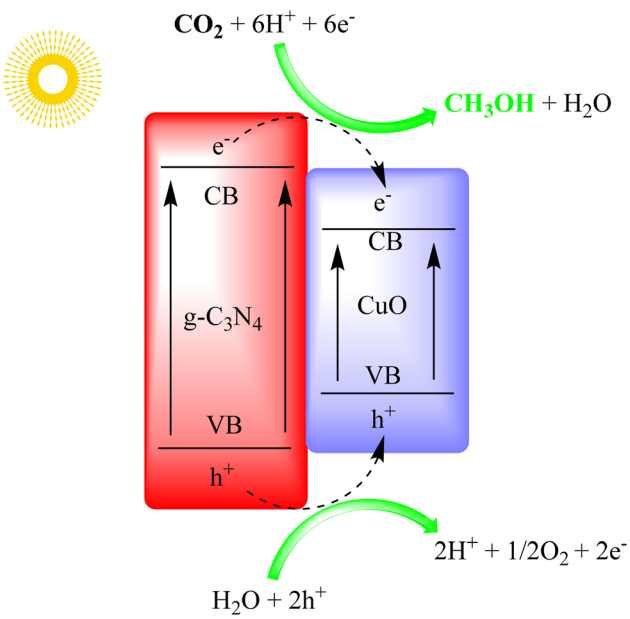


Fig. 18 g-C_3N_4/CuO heterostructure for photo electrocatalytic CO_2 reduction under visible light irradiation.

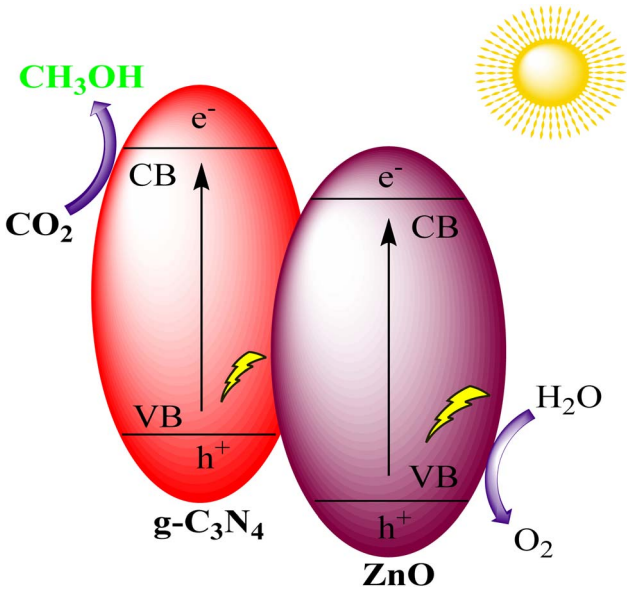


Fig. 19 g-C_3N_4/ZnO heterostructure for photocatalytic CO_2 reduction under visible light irradiation.

driven CO_2 reduction. The catalyst's multifunctionality, promoting hydrogen generation, CO_2 activation, and minimizing electron–hole recombination, demonstrates promise for high-yield, room-temperature, and normal-pressure photocatalytic CO_2 reduction. Khan *et al.*'s CuO/g-C_3N_4 photocathode excels in producing methanol *via* photoelectrochemical reduction of CO_2, showcasing a tenfold increase in the photocurrent response and improved faradaic and quantum efficiency. Yu *et al.*'s Z-scheme g-C_3N_4/ZnO composite offers enhanced light absorption and a 2.3-fold increase in catalyzing CO_2 conversion to CH_3OH, highlighting its potential for efficient CO_2 reduction. Pant and co-authors' TiO_2/g-C_3N_4 heterostructure demonstrates the importance of charge separation, yielding higher methanol production compared to individual components. These studies collectively contribute valuable insights into designing

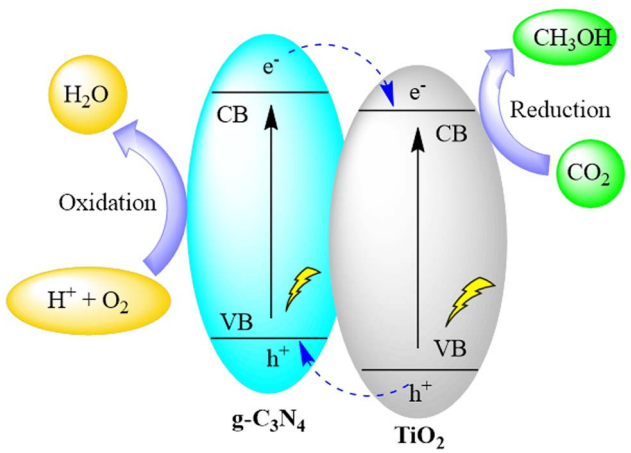


Fig. 20 g-C_3N_4/TiO_2 heterostructure for photocatalytic CO_2 reduction under visible light irradiation.

efficient photocatalysts for diverse applications in CO_2 reduction (Table 5).

In the ambitious endeavor to combat climate change and harness solar energy, g-C_3N_4 emerges as a beacon of innovation and sustainability in the realm of solar-driven carbon dioxide reduction. Its capacity to convert the ubiquitous greenhouse gas, carbon dioxide, into valuable hydrocarbons and chemicals represents a profound stride towards a carbon-neutral future. As we confront the urgent need to reduce carbon emissions and transition to renewable energy sources, g-C_3N_4 embodies the promise of a cleaner, more sustainable world. With the absorption of each photon and transformation of each carbon dioxide molecule, it not only mitigates climate change but also offers a glimpse into the boundless possibilities of harnessing solar energy for a greener tomorrow. In the intersection of environmental preservation and renewable energy, g-C_3N_4's role in solar-driven carbon dioxide reduction is a testament to our commitment to a more sustainable, carbon-conscious, and brighter future.

5.6 Solar fuel cells

Solar fuel cells represent a vital component of the renewable energy landscape. g-C_3N_4's ability to generate hydrogen and other energy carriers through photocatalysis aligns with the development of solar fuel cells. These cells can store and utilize solar energy for power generation and transportation, reducing reliance on fossil fuels and minimizing greenhouse gas emissions.

Liu *et al.* developed a visible-light-driven photocatalytic fuel cell (PFC) that efficiently degrades tetracycline hydrochloride (TC) and generates electricity in a single reactor. The PFC used paired stainless-steel mesh electrodes loaded with specific catalysts under different conditions, with and without visible light. With visible light, TC removal was highly effective (97.3% in 90 minutes), with a cell voltage of 0.98 V and 24 W m^{-2} power density. Simultaneous removal of chemical oxygen demand (COD) and total organic carbon (TOC) was notable, driven by the anodic g-C_3N_4/Fe^0 (1%)/TiO_2 component. Without light, performance dropped significantly, but the PFC continued to operate as a self-driven system, degrading pollutants. The PFC maintained its performance over multiple cycles with light, offering potential for wastewater treatment. In the dark, it still generated electricity but at reduced capacity. This research shows promise for efficient pollutant removal and energy recovery in wastewater treatment, as shown in Fig. 21.[105,106]

Zhang *et al.* significantly enhanced the performance of carbon-based perovskite solar cells without a hole-transporting material (HTM). They achieved a power conversion efficiency (PCE) above 14% by introducing g-C_3N_4 doping and an Al_2O_3 insulating layer, as depicted in Fig. 22. g-C_3N_4 improved the perovskite film quality, and with just 0.5 wt% g-C_3N_4 doping, the PCE increased to 12.85%. The Al_2O_3 insulating layer enhanced open-circuit voltage (V_{oc}) and further increased PCE to 14.34% by reducing recombination at the ETM/perovskite interface. The resulting device demonstrated good stability, offering potential for cost-effective, high-performance

Table 5 Solar-driven carbon dioxide reduction *via* g-C_3N_4-based catalytic systems

Entry	Catalyst	Conditions	Productivity	Reference material	Ref.
1	$Pt/In_2O_3/g\text{-}C_3N_4$	20 mg catalyst, 1 atm CO_2, 10 mL H_2O, 1 mL TEOA, 35 °C, 4 h, 3 W LED (420 nm)	HCOOH – 63.1, CH_4 – 7.907 (μmol g^{-1} h^{-1})	NA	101
2	$CuO/g\text{-}C_3N_4$	(Nafion/$CuO/g\text{-}C_3N_4$), $NaHCO_3$ (0.1 M), bias potential illumination	25.1 (μmol L^{-1} cm^{-2})	5.92 (μmol L^{-1} cm^{-2})	102
3	$ZnO/g\text{-}C_3N_4$	100 mg sample in 10 mL deionized water, 80 °C, 0.12 g $NaHCO_3$, 0.25 mL 4 M HCl, 300 W Xe arc lamp	0.60 (μmol g^{-1} h^{-1})	0.26 (μmol g^{-1} h^{-1})	103
4	$TiO_2/g\text{-}C_3N_4$	0.2 g of catalyst, high purity CO_2, 0.2 g of catalyst, 200 mL of 0.1 M NaOH, 250 W halogen lamp	31.7 (μmol g^{-1})	14.1 (μmol g^{-1})	104

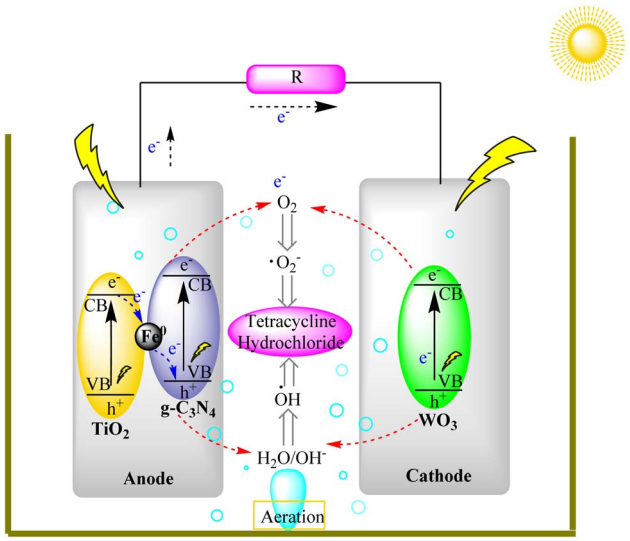


Fig. 21 Visible-light-driven photocatalytic fuel cell (PFC).

perovskite solar cells without a HTM, which could have a significant impact on the market.[107,108]

Wang and collaborators synthesized a Z-scheme photocatalyst, Ag_3PO_4@g-C_3N_4, which served as the photoanode in a photoelectro-Fenton (PFC) system alongside Cu_2O as the photocathode, as illustrated in Fig. 23. The Z-scheme structure was deliberately designed to ensure effective separation of charge carriers, thereby enhancing the overall PFC performance. Furthermore, the catalyst exhibited a high redox ability, actively participating in the degradation of organic pollutants. The electricity production of the PFC system was observed to increase with N_2 aeration, while O_2 purging proved beneficial for the photocatalytic degradation of organic pollutants. The study highlights the efficacy of the Z-scheme photocatalyst in achieving efficient charge separation and contributing to the effective degradation of organic pollutants in a PFC system.[109]

Liu *et al.*'s visible-light-driven photocatalytic fuel cell (PFC) efficiently degrades tetracycline hydrochloride (TC) and generates electricity, demonstrating a promising approach for simultaneous wastewater treatment and energy recovery. The PFC, operating under visible light, achieves high TC removal, and COD, and TOC reduction, showcasing its potential for sustainable wastewater treatment with electricity generation. Zhang *et al.*'s work on carbon-based perovskite solar cells with g-C_3N_4 doping and an Al_2O_3 insulating layer enhances power conversion efficiency (PCE) to over 14%, offering a cost-effective and stable solution for high-performance solar cells without a hole-transporting material (HTM). Finally, Wang *et al.*'s Z-scheme Ag_3PO_4@g-C_3N_4 photocatalyst in a photoelectro-

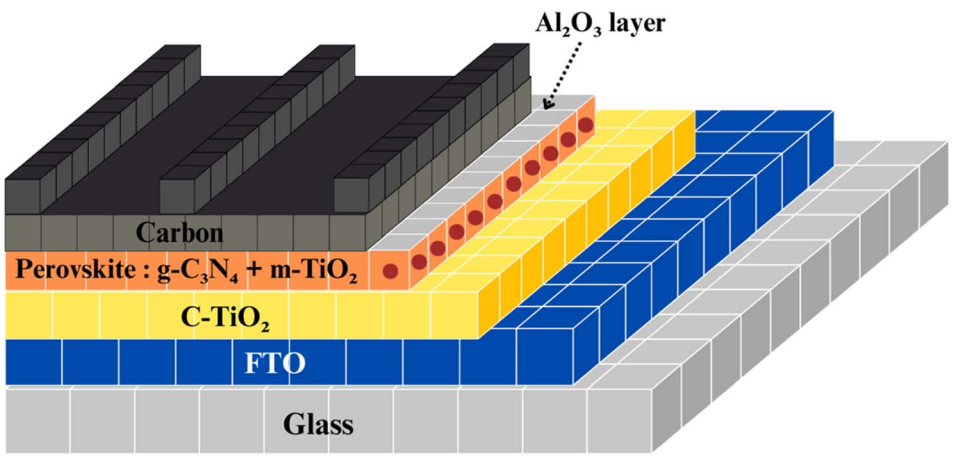


Fig. 22 Al_2O_3 layer insulated g-C_3N_4 added carbon-based perovskite solar cells.

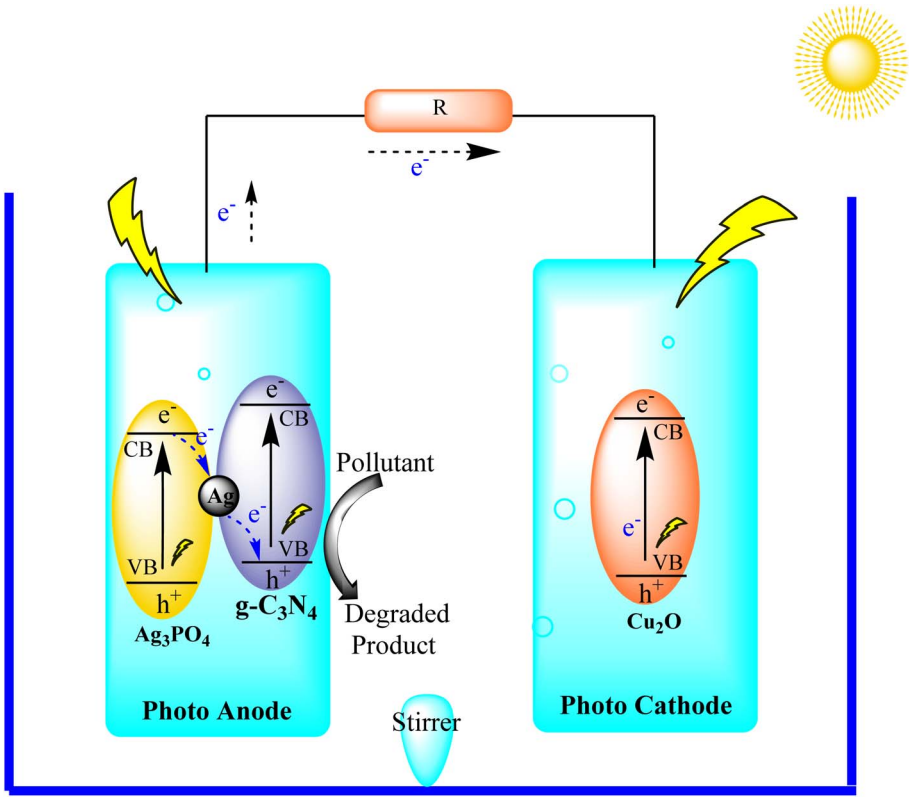


Fig. 23 Z-scheme Ag_3PO_4@g-C_3N_4 photocatalyst for fuel cell synthesis.

Fenton (PFC) system demonstrates efficient charge separation and active participation in organic pollutant degradation, emphasizing its potential for environmentally friendly energy production and wastewater treatment. These studies collectively showcase the versatile applications of g-C_3N_4 in advancing sustainable technologies (Table 6).

As we strive for a future powered by clean and renewable energy, g-C_3N_4 emerges as a pivotal player in the realm of solar fuel cells. Its remarkable ability to harness sunlight and catalyze the conversion of solar energy into clean fuels holds the key to reducing our reliance on fossil fuels and mitigating climate change. With each electron it liberates and each hydrogen molecule it generates, g-C_3N_4 not only powers our aspirations for a sustainable energy landscape but also illuminates the path toward a greener, more promising future. In the synergy of advanced technology and environmental responsibility, g-C_3N_4's role in solar fuel cells is a testament to our commitment to a world where clean energy sources drive our progress, ushering in an era of energy sustainability and environmental preservation.

Each of these applications of g-C_3N_4 as a photocatalyst embodies a sustainable approach to addressing environmental and energy challenges. Specific case studies and examples underscore the material's effectiveness in various contexts. Furthermore, the environmental benefits, such as reduced energy consumption and lower pollutant emissions, coupled with potential economic advantages, position g-C_3N_4 as a pivotal catalyst for a cleaner, more sustainable future.

Table 6 g-C_3N_4-based perovskite fuel cells for photovoltaic performance

Entry	System	Conditions	Current density	Fuels	Ref.
1	Ag_3PO_4@g-C_3N_4	Photocatalytic fuel cell (50 mg of photocatalyst, 10 mg L^{-1} berberine chloride, 50 W Xe lamp)	2.02 mA cm^{-2}	Berberine chloride	109
2	FTO/c-TiO_2/m-TiO_2/perovskite: g-C_3N_4/carbon	FTO/c-TiO_2/m-TiO_2/perovskite: g-C_3N_4/carbon device	(Perovskite) 21.5 mA cm^{-2} (0.5 wt% g-C_3N_4/perovskite) 24.0 mA cm^{-2}	NA	107
3	g-C_3N_4/FeO/TiO_2	0.05 g of photocatalyst, 100 mL of TC (10 mg L^{-1}), Na_2SO_4 (0.1 mol L^{-1}), 300 W Xe lamp	6.06 μW cm^{-2} 0.067 μW cm^{-2}	Rhodamine-B Methylene blue Tetracycline	105

6. Challenges and future prospecs

Graphitic carbon nitride (g-C_3N_4) undoubtedly exhibits exceptional photocatalytic capabilities, yet several challenges warrant attention as we aim to harness its full potential. Foremost among these challenges is the need to enhance its quantum efficiency—the efficiency with which it utilizes incoming photons. Researchers are actively working to minimize electron–hole pair recombination rates and boost the overall photocatalytic conversion efficiency. Additionally, ensuring photostability over extended usage periods is critical. Factors such as photo-corrosion and aggregation can impact g-C_3N_4's performance, necessitating the development of stable g-C_3N_4 materials and protective coatings. Achieving high selectivity in complex reaction mixtures remains a formidable challenge, even though g-C_3N_4 exhibits remarkable selectivity in many reactions. Fine-tuning the material's surface properties and optimizing reaction conditions continue to be areas of investigation. Finally, scaling up g-C_3N_4 production from laboratory-scale to practical, large-scale applications presents logistical challenges, requiring cost-effective manufacturing methods and seamless integration into the existing infrastructure.

The future prospects for g-C_3N_4 photocatalysis are exceptionally promising, driven by ongoing research and innovative strategies. The integration of advanced co-catalysts, such as metal nanoparticles or semiconductor materials, holds the potential to significantly enhance charge separation and overall photocatalytic performance. The tailoring of g-C_3N_4 materials with specific structural and electronic properties optimized for various applications is another exciting avenue of exploration, allowing for custom-designed photocatalysts. These developments pave the way for tailored solutions to environmental and energy challenges. Moreover, the integration of g-C_3N_4 photocatalysis with solar cell technologies in tandem or integrated systems offers the possibility of continuous and efficient energy conversion. The exploration of g-C_3N_4's application in environmental remediation, such as addressing emerging pollutants like pharmaceuticals and microplastics in water and air, remains an area of interest. Additionally, the concept of artificial photosynthesis systems, where g-C_3N_4 plays a pivotal role in replicating natural photosynthesis for sustainable fuel production and carbon capture, holds immense promise. As the world continues to prioritize environmental sustainability and clean energy, g-C_3N_4 remains poised at the forefront of these advancements, representing a cornerstone in the journey toward a greener and more sustainable future.

7. Conclusion

In this comprehensive review, we have delved into the multifaceted world of graphitic carbon nitride (g-C_3N_4) as a promising photocatalyst, exploring its diverse synthesis methods, unique structural properties, intricate photocatalytic mechanisms, and transformative applications in sustainability. We've navigated through its pivotal role in various domains, from organic transformations and hydrogen production through water splitting to water purification, air purification, solar-driven carbon dioxide reduction, and solar fuel cells. Throughout our journey, we've highlighted the environmental and economic benefits of g-C_3N_4 in these applications. As we conclude, it's evident that g-C_3N_4's innovative potential holds the promise of a cleaner, more sustainable future, making it a beacon of hope in the intersection of science and environmental stewardship.

Conflicts of interest

The authors declare that they have no conflict of interest.

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