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Progress and challenges in photocatalytic ammonia synthesis

The group of Solar Energy and Advanced Materials, led by Prof. Junwang Tang focuses on photocatalytic small molecule activation (including CH_4 , N_2 , H_2O , C_6H_6 and CO_2) to high-value chemicals/fuels and microwave catalysis (e.g. plastic chemical recycling), together with microwave-intensified chemical processes. In parallel, the group has state-of-the-art spectroscopies to investigate the underlying charge dynamics and kinetics. This review puts forward a few critical issues existing in nitrogen photoreduction, along with a comprehensive discussion of strategies for improvement of NH_3 yield, aiming to make substantial contribution towards advancing this field.



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REVIEW

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Progress and challenges in photocatalytic ammonia synthesis

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Photocatalytic ammonia (NH₃) synthesis from N₂ and water driven by solar energy is a sustainable and environmentally friendly technology, which has gained considerable attention in recent years. In this review, the recent development in the fundamental understanding of photocatalytic NH₃ synthesis and the methods of precise NH₃ detection are summarized. More importantly the strategy for surface engineering and interface engineering of photocatalysts toward photocatalytic NH₃ production has been thoroughly analyzed with the aim to stimulate critical thinking about the effective methodology for catalyst modification instead of exploring new materials. At the end the challenges and a few concerns are raised from the current reports and future perspectives in this research field are discussed targeting to clarify the reliability and reproducibility of the photochemical process and to direct the future research direction, such as flow reactor design and in-depth understanding of the underlying reaction pathway.

highly desirable but challenging.

Introduction

Ammonia (NH₃) has been regarded as one of the most important chemical products as feedstock for fertilizers and for various chemicals.^{1,2} The production of NH₃ plays a prominent role in global economy with an annual yield of more than 200 million tons.³ The industrial synthesis of NH₃ is dominated

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by the revolutionary Haber-Bosch process, in which pure H₂

and N₂ are reacted under high pressure at high temperature

over Fe-based catalysts, which consumes 1-2% of total global

fossil fuels and releases around 300 million tons of planet-

warming CO₂ into the atmosphere annually.⁴⁻⁷ The develop-

ment of environmentally friendly, sustainable strategies with

high efficiency of NH₃ production under mild conditions is

synthesis. One is biological nitrogen fixation which mostly

relies on diazotrophs in nature.8 Another one is electrochemical

reduction of N2, which uses electricity to produce NH3.9,10

Compared with the stringent conditions of biological nitrogen

fixation and the requirement of highly conductive electrolytes

Currently, there are a few green routes reported for ammonia

and costly electrodes used in electrochemical reduction of N₂, photocatalytic ammonia synthesis using sustainable solar energy operated under either aqueous or gaseous conditions is rather different, maybe also economical, from the other methods. If the efficiency of solar driven NH₃ synthesis could be dramatically improved, this method has strong potential to replace the current Haber-Bosch process. Photocatalytic reduction of N₂ to produce NH₃ by utilizing photocatalysts and water, driven by renewable solar energy, has huge potential, and thereby is very significant.^{11–17} Since the seminal work of Schrauzer and Guth in 1977,¹⁷ in which the potential of the TiO₂ photocatalyst for N₂ reduction with water and N₂ was revealed, various semiconductors have been studied for the photocatalytic production of NH₃, such as ZnO, Fe₂O₃, Ga₂O₃, W18O49, BiOBr, BiOCl, CdS, layered double hydroxides, polymeric carbon nitride and so on.¹⁸⁻²⁵ The main challenges for the photocatalytic synthesis of NH₃ are the chemical adsorption and activation of N₂. To boost the efficiency of NH₃ photosynthesis, the exploitation of highly active photocatalytic materials is crucial. Through surface/interface engineering of various photocatalysts, the photocatalytic reaction pathways can be modulated, therefore enhancing the N2 reduction reaction activity.

Complementary to other reviews in which different photocatalysts are summarized,^{6,13,18,19,22} this crucial review tries to avoid simply listing a large population of materials and mainly concentrates on recent advances and understanding in two fast moving areas, *i.e.* surface engineering and interface engineering, which have been proved to be efficient strategies to improve most photocatalysts' activity for NH₃ synthesis, including defect engineering, morphology engineering, cocatalyst loading, and junction structure. The materials stated here are representative and highly efficient. Thus, this review aims at providing a comprehensive understanding of the rational design of highly efficient photocatalysts for N_2 photoreduction. Apart from this, the recent understanding of the photocatalytic mechanism of NH_3 synthesis and the methods to precisely evaluate the catalytic performance of a photocatalyst in NH_3 synthesis will be discussed. Future research directions for further development of the photocatalytic synthesis of NH_3 and some concerns will be highlighted at the end.

Photocatalytic mechanism of NH₃ synthesis

By mimicking the natural process of photosynthesis, researchers intend to convert solar energy, N_2 and water to NH_3 by using photocatalysts. The overall reaction is listed as follows:

$$2N_2 + 6H_2O \rightarrow 4NH_3 + 3O_2$$

In this artificial photosynthesis, there are two interlinked conversion processes, water splitting and N_2 reduction reaction (NRR).²⁶ As shown in Fig. 1a, upon light irradiation, photoinduced electrons generated from photocatalysts populate the conduction band, leaving holes in the valence band. Subsequently, the escaped electrons diffuse across to the reactive sites on the surface of photocatalysts. The adsorbed N_2 and H_2O are catalyzed by these electrons and holes into NH₃ and O_2 , respectively, along with the generation of the byproduct H_2 . Thus the key point for this process is not only to design a highly active photocatalyst but also to achieve high selectivity to NH₃ instead of H_2 gas as indicated in Fig. 1a.



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Fig. 1 (a) Photocatalytic synthesis of NH_3 in water. (b) The proposed mechanisms for photocatalytic N_2 reduction consisting of the dissociative pathway, the associative alternating pathway, and the associative distal pathway. Reproduced from ref. 27 with permission from ACS Publication. (c) The proposed mechanism of surface-hydrogenation over noble metal doped photocatalysts for NRR. Reproduced from ref. 28 with permission from ACS Publication.

Up to now, the mechanisms for N₂ reduction to NH₃ on photocatalysts have been divided into two categories based on the surface adsorption characteristics of catalysts: N-hydrogenation (Fig. 1b) and surface-hydrogenation (Fig. 1c).^{27,28} For the *N*-hydrogenation mechanism, there are two different pathways for NRR, dissociative and associative pathways. In the dissociative pathway, the N₂ triple bond is broken before hydrogenation, followed by hydrogenation of the N-adatoms into NH₃ on the catalyst surface. The Haber-Bosch process is proved to be the dissociative pathway, which requires prohibitively high energy to cleave the N=N bond. Compared with the dissociative pathway, the associative pathway without the breaking of the $N \equiv N$ bond is generally used and accepted far more in the photocatalytic NRR. The nitrogen surface adsorption configuration determines the associative pathways for NRR; as shown in Fig. 1b, the hydrogenation of the adsorbed N₂ preferentially occurs at the terminal-site N owing to its relatively low steric hindrance for both the associative alternative pathway and the associative distal pathway. Having generated the first NH₃, the other N begins a new hydrogenation circulation to produce a second NH₃. It is actually impossible to identify the N₂ configurations due to the fact that they are favored equally by the catalysts.

Recently, a novel surface-hydrogenation mechanism for NRR has been proposed (Fig. 1c),²⁸ in which the adsorbed H^+ is reduced into *H first, and then N₂ molecules react with surface *H to generate *N₂H₂, and finally the formed *N₂H₂

intermediates are reduced into NH₃. The first step is the trigger step, which enables the NRR to occur at a low potential. Furthermore, the second step is the rate determining step because it needs to conquer a high energy barrier (E_a) to break the N \equiv N bond. The E_a of hydrogen evolution reaction is always lower than that of NRR, and therefore the NH₃ production rate is relatively low.

As a complete cycle indicated in Fig. 1a is the ideal process but very challenging, in most cases (or in the majority of the reported cases), a half reaction was investigated in which N_2 was reduced to NH_3 in the presence of an efficient hole scavenger which was oxidized other than water oxidation. This half reaction is relatively easy and can be used to preliminarily scan different photocatalysts for N_2 reduction. Bear in mind that this half reaction has advantages but does not indicate whether the photocatalyst selected is good for a complete cycle as indicated in Fig. 1a. The subsequent discussion will underline this in order to remind the audience of the large difference between a half reaction and the complete cycle.

Determination of NH₃

 NH_3 detection is a necessary subject for the photocatalytic synthesis of NH_3 , which is of great significance in the design of high performance photocatalysts. There are four common methods of NH_3 analysis such as colorimetric assays, ¹⁵N



Fig. 2 Photographs of NH₃ solution with different concentrations (0, 1.2, and 4 mg L^{-1} from left to right) when (a) mixing with Nessler's reagent and (b) adding 4 µg L^{-1} formaldehyde into the above ammonia solution with Nessler's reagent. Measured results of NH₃ concentration using (c) Nessler's reagent and d) ion chromatography methods. Reproduced from ref. 29 with permission from ACS Publication. (e) The NH₃ concentration evolution with time tested by ion chromatography. Inset in (e): UV-vis absorption spectra tested with the indophenol reagent with the characteristic adsorption peak of 630 nm wavelength. Reproduced from ref. 30 with permission from ACS Publication.

isotope labeling, ion chromatography, and in situ infrared spectroscopic measurements.¹² The colorimetric assays include Nessler, phenate, and indophenol blue tests for NH₃ detection. Among the colorimetric assays, Nessler's reagent has been widely used in NH₃ detection due to its advantages of simplicity and low cost.²⁹ However, it is reported that the sacrificial agents (*i.e.*, alcohol) used in the photocatalytic synthesis of NH₃ systems can be oxidized to carbonyl compounds, which will disturb NH₃ detection in Nessler's reagent detection, thus yielding misleading results. Fig. 2a shows photographs of a solution containing Nessler's reagent and different concentrations of NH₃ solutions (0, 1.2, and 4 mg L^{-1}).²⁹ It can be seen that the solution color is turning from light yellow to brown with the increase in the concentration of NH₃. When 4 μ g L⁻¹ of formaldehyde is added, all the above solutions change into brown, indicating that trace formaldehyde can cause a remarkable color change (Fig. 2b). Therefore, the method of Nessler's reagent is not able to detect NH₃ production in the presence of this or similar sacrificial agents. In contrast, the generated carbonyl compounds have no effect on the testing method of ion chromatography (Fig. 2c and d). It is strongly recommended that the colorimetric assay methods have to be accompanied by other methods such as ion chromatography, ¹⁵N isotope labeling, and in situ infrared spectroscopic measurements, to

avoid such misleading results. Fig. 2e shows the photocatalytic performance of NH_3 synthesis *via* ion chromatography and the indophenol test.³⁰ The UV-vis spectra of the reaction solution containing NH_3 exhibit a maximum absorption at 630 nm (inset in Fig. 2e), which is ascribed to the indophenols. The production of NH_3 measured by ion chromatography increases with the reaction time (Fig. 2e), consistent with the results obtained by the indophenol test, indicating that indophenol is to some extent reliable.

Extensive studies on the determination of NH_3 have revealed that the indophenol blue method, Nessler's reagent method, and the ion chromatography method are accurate when the concentration of NH_3 is less than 500 µg L⁻¹, but the indophenol blue method tends to be less accurate at higher concentrations or under acidic conditions. Besides, the presence of carbonyl compounds from scavengers will enhance light adsorption in Nessler's reagent method, thus leading to an interfered detection of NH_3 . Thus, to guarantee accuracy and reliability of NH_3 quantification, at least two detection methods such as the ion chromatography method and Nessler's reagent method are recommended. Furthermore, because of trace NH_3 in the ambient atmosphere, it is necessary to test the isotopically labeled ${}^{15}N_2$ to confirm the source of nitrogen in the product.

Strategies to improve photocatalytic efficiency

As mentioned above there are a few reviews summarizing the activity of diverse photocatalysts.^{6,13,18,19,22} This critical review will not overlap with these reviews, but will only concentrate on the efficient strategies to improve (i) N2 adsorption and (ii) charge separation. Such strategies include surface engineering and interface engineering for NH₃ synthesis. The photocatalytic process of NH₃ production generally includes four steps, photogeneration of charge carriers followed by their migration to the active sites, N2 chemisorption, surface photo-oxidation and photo-reduction, and the desorption NH₃ from photocatalysts. Following the above key steps, photocatalysts can be engineered to greatly promote their catalytic activities toward NH₃ synthesis. As steps (ii), (iii) and (iv) all take place on the surface, through the study of surface regulations and interface modulations on the photocatalysts, their photocatalytic performance can be maneuvered. The surface regulations, including defect engineering and morphology engineering, significantly determine the photocatalytic activity because they can promote the surface adsorption and activation of N_2 .^{23,31-40,54-57,64-71} The interface modulations, including modification with cocatalysts and semiconductors, greatly affect the charge transfer and separation efficiency.^{89–101,109–111} We will discuss these factors one by one below. In order to provide an intuitively systematic comparison of photocatalytic N2 reduction systems, we list photocatalysts, reactants, NH₃ production rate, in particular the apparent quantum efficiency and detection method as shown in Table 1.

Surface regulations

Defect engineering. It is widely reported that vacancies in a photocatalyst can improve N_2 adsorption, to some extent even charge separation. There are different populations of vacancies, including oxygen vacancies, nitrogen vacancies, carbon vacancies, as well as sulfur vacancies.

Oxygen vacancies. The introduction of oxygen vacancies (OVs) can effectively facilitate N2 adsorption and activation, as well as induce the generation of mid-gap states to promote the separation of photogenerated charge carriers.³¹⁻⁴² For instance, Zhang et al. reported that BiOBr nanosheets with OVs on the exposed {001} facets (BOB-001-OV) could stretch the $N \equiv N$ bonds from 1.078 Å to 1.133 Å, which gave strong evidence for N₂ activation over the OVs.³¹ Theoretical calculations showed that the OV induced defect states could serve as the electron acceptor (Fig. 3a) to effectively suppress the recombination of electrons/holes and enhance the charge transfer from BOB-001-OV to the N2 molecule. Fluorescence spectroscopy showed that the average lifetime (τ) of BOB-001-OV was 2.15 ns, around two times higher than that of BiOBr without OVs (BOB-001-H, Fig. 3b), proving that the OVs could promote the migration of charge carriers. With the function of OVs, BOB-001-OV showed a NH₃ yield rate of 104.3 μ mol g⁻¹ h⁻¹ under visible light illumination in the absence of organic scavengers

and noble-metal cocatalysts (Fig. 3c), and an apparent quantum efficiency (AQE) of 0.23% at 420 nm. Meanwhile, the amount of generated O_2 was stoichiometrically approaching 3/4 of the produced NH₃, which proved that water could act as an electron donor to achieve a complete chemical cycle in NH₃ photosynthesis.

Apart from the research on bismuth oxyhalide materials, Shiraishi's group utilized a series of commercial TiO_2 to study the effect of OVs on the photoreduction of N_2 to NH_3 .³² A commercial TiO_2 of JRC-TIO-6 showed an excellent performance with a steadily increasing NH_3 production within 100 h under UV light irradiation in pure water. They proposed that the Ti^{3+} species formed at the OVs on the surface of TiO_2 served as active sites, which could effectively trap the electrons and promote N_2 dissociation, resulting in a photocatalytic NH_3 production rate of 2.5 μ mol h⁻¹.

In order to create the OVs, most studies used oxygencontaining catalysts. In recent years, layered double hydroxide (LDH, Fig. 4a) materials have attracted substantial attention due to their tunable electron structure and low cost.³⁴ Zhang's group firstly used the CuCr-LDH nanosheets (CuCr-NS) with OVs as efficient photocatalysts for NH₃ photosynthesis.³⁴ The OVs over CuCr-NS surface were created by the reduction of thickness and the in-plane compressive strain (Fig. 4b). The optimal CuCr-NS exhibited a NH₃ production rate of 78.6 μ mol g⁻¹ h⁻¹ under full-spectrum irradiation (Fig. 4c), and an AQE of 2.4% at 400 nm. Subsequently, they further reported another work on ZnAl-LDH nanosheets for optimal OVs by incorporating coordinately unsaturated $Cu^{\delta+}$ species.³⁵ The DFT calculations implied that the OVs and Cu^{δ^+} species in ZnAl-LDH could effectively promote N₂ adsorption and activation, leading to a remarkable NH₃ yield of 110 μ mol L⁻¹ h⁻¹ in pure water under UV-vis irradiation. Therefore, the creation of OVs on the surface of photocatalysts paves a way for developing other innovative materials toward photocatalytic N₂ reduction.

Nitrogen vacancies/carbon vacancies. Inspired by the conclusion of N2 activation and efficient electron transfer by OVs on the catalyst surface, nitrogen vacancies (NVs) were later studied for the NRR process. Because of its excellent optical properties, low cost, and good stability, graphitic carbon nitride $(g-C_3N_4)$ has attracted much scientific interest in the field of photocatalysis.^{42–53} Dong et al. have reported the application of NV-incorporated g-C₃N₄ (V-g-C₃N₄) for N₂ photoreduction.⁵⁴ They found that the N₂ adsorption amount of V-g-C₃N₄ was 75.1 cm³ g⁻¹, 2.4 times higher than that of g-C₃N₄ without NVs $(30.9 \text{ cm}^3 \text{ g}^{-1})$, which suggested that the NVs on the surface of V-g-C₃N₄ could provide a number of chemisorption and activation sites for N2 molecules, leading to an NH3 production rate of 1.24 mmol $h^{-1} g_{cat}^{-1}$ under visible light irradiation in the presence of methanol as a hole scavenger. Recently, a g- C_3N_4 catalyst modified with cyano groups (-C \equiv N) and intercalated K⁺ (mCNN) was prepared as an efficient photocatalyst for NRR.⁵⁵ Relative to pristine g-C₃N₄, the absorption spectrum of mCNN was extended to the whole visible region (Fig. 5a), resulting from the π - π * electronic transitions in the conjugated heterocyclic rings and the $n-\pi^*$ electronic transitions at the

Table 1	Photocatalyt	ic performanc	e of different	catalysts for	NH ₇ synthesis
Tuble 1	Thorocalary	e periornane	e or annerent	catalysts for	This Synchesis

Catalyst	Reaction medium	Scavenger	Light source	Ammonia yield	Apparent quantum efficiency (AQE)	Ammonia detection method	Ref.
BiOBr-001-OV JRC-TIO-6 CuCr-LDH	$\begin{array}{l} N_2/H_2O \left(l \right) \\ N_2/H_2O \left(l \right) \\ N_2/H_2O \left(l \right) \end{array}$	None 2-PrOH None	$\lambda > 420 \text{ nm}$ $\lambda > 280 \text{ nm}$ Full	104.3 μ mol g ⁻¹ h ⁻¹ 2.5 μ mol g ⁻¹ h ⁻¹ 78.6 μ mol g ⁻¹ h ⁻¹	0.23% at 420 nm Not reported 2.4% at 400 nm	Nessler's reagent Indophenol blue method Nessler's reagent	31 32 34
ZnAl-LDH	$N_2/H_2O\left(l\right)$	None	UV-vis	110 $\mu mol \ L^{-1} \ h^{-1}$	1.77% at 265 nm,	Ion chromatography	35
V-g-C ₃ N ₄ mCNN	N ₂ /H ₂ O (l) N ₂ /ethylene	Methanol Ethylene	$\lambda > 420 \text{ nm}$ $\lambda > 400 \text{ nm}$	1.24 mmol $h^{-1} g_{cat}^{-1}$ 3.42 mmol $g^{-1} h^{-1}$	Not reported Not reported	Nessler's reagent Nessler's reagent	54 55
SCNNSs	$M_2/H_2O(l)$	giycol Methanol	Full	$5.99 \text{ mmol h}^{-1} \text{g}_{\text{cat}}^{-1}$	Not reported	Nessler's reagent	56
Mo _{0.1} Ni _{0.1} Cd _{0.8} S 0.2 wt% Fe-doped TiO ₂	$N_2/H_2O(l)$ $N_2/H_2O(g)$	Ethanol None	UV UV	$\begin{array}{l} 3.2 \ \text{mg} \ h^{-1} \ g_{cat}^{-1} \\ 11.6 \ \mu \text{mol} \ g^{-1} \ h^{-1} \end{array}$	Not reported Not reported	Nessler's reagent Indophenol blue method	57 17
0.4 wt% Co-doped	$l N_2/H_2O(l)$	None	UV	6.3 μ mol g ⁻¹ h ⁻¹	Not reported	Indophenol blue method	17
0.4 wt% Cr-doped	$N_2/H_2O(l)$	None	UV	$0.37 \ \mu mol \ g^{-1} \ h^{-1}$	Not reported	Indophenol blue method	17
0.4 wt% Mo- doped TiO ₂	$N_2/H_2O\left(l\right)$	None	UV	6.7 $\mu mol g^{-1} h^{-1}$	Not reported	Indophenol blue method	17
Fe-Doped TiO ₂ Fe-Doped SrMoO ₄	$N_2/H_2O(l) N_2/H_2O(l)$	Ethanol None	$\lambda = 254 \text{ nm}$ UV-vis	$\begin{array}{l} \text{1.2 mmol } L^{-1} \\ \text{93.1 } \mu \text{mol } g^{-1} \ h^{-1} \end{array}$	Not reported Not reported	Nessler's reagent Nessler's reagent, indophenol blue method	64 65
Fe-Doped BiOCl	$N_2/H_2O\left(l\right)$	None	Full	$1.022 \text{ mmol g}^{-1} \text{ h}^{-1}$	1.8% at 420 nm	Indophenol blue method	66
Mo-Doped W ₁₈ O ₄₉	$_{0}$ N ₂ /H ₂ O (l)	Na_2SO_3	Full	195.5 μ mol g ⁻¹ h ⁻¹	0.33% at 400 nm	Nessler's reagent, ion	67
Cu-Doped TiO ₂	$N_2/H_2O\left(l\right)$	None	Full	78.9 $\mu mol \ g^{-1} \ h^{-1}$	0.08% at 600 nm, 0.05% at 700 nm	Nessler's reagent, ion	68
FePt@C ₃ N ₄	N_2/H_2	None	$\lambda > 400 \text{ nm}$	$63 \ \mu g \ h^{-1} \ g^{-1}$	0.15% between 450 and 500 nm	Colorimetric method, ion	72
B-Doped g-C ₃ N ₄ C-Doped TiO ₂	$N_2/H_2O(l)$ $N_2/H_2O(l)$	Na_2SO_3 Methanol	$\lambda > 400 \text{ nm}$ $\lambda > 420 \text{ nm}$	313.9 μ mol g ⁻¹ h ⁻¹ 109 3 μ mol g ⁻¹ h ⁻¹	0.64% at 420 nm	Nessler's reagent	73
Bi _z O _z I-001	$N_2/H_2O(l)$	Methanol	280-800 nm	$105.5 \ \mu mol g^{-1} h^{-1}$	5.1% at 365 nm	Nessler's reagent	77
BiOCl-010	$N_2/H_2O(l)$	Methanol	Full	92.4 μ mol g ⁻¹ h ⁻¹	4.3% at 254 nm	Nessler's reagent	78
BiO	$N_2/H_2O\left(l\right)$	None	Full	1226 $\mu mol \ g^{-1} \ h^{-1}$	Not reported	Indophenol blue method	86
Bi₂O₂Br-NT	$N_2/H_2O(l)$	None	$\lambda > 400 \text{ nm}$	$1.38 \text{ mmol g}^{-1} \text{ h}^{-1}$	2.3% at 420 nm	Nessler's reagent	87
eBP NFs	$N_2/H_2O(l)$ $N_2/H_2O(l)$	Na ₂ SO ₃ , Na ₂ S·	$\lambda = 420 \text{ nm}$	2.37 mmol g^{-1} h ⁻¹	Not reported	Nessler's reagent	88
SiO ₂ /C-RP	$N_2/H_2O\left(l\right)$	None	Full	0.73 μ mol h ⁻¹	Not reported	Ion chromatography	89
Ru-Loaded TiO ₂	$N_2/H_2O\left(l\right)$	Methanol	Full	$29.4 \ \mu mol \ g^{-1} \ h^{-1}$	Not reported	Indophenol blue method	93
Ru-Loaded TiO ₂	$N_2/H_2O\left(l\right)$	Ethanol	Full	56.3 $\mu g \; h^{-1} \; {g_{cat}}^{-1}$	Not reported	Indophenol blue method	95
Au/TiO ₂ -OV	$N_2/H_2O(l)$	Methanol	$\lambda > 420 \text{ nm}$	78.6 μ mol g ⁻¹ h ⁻¹	0.82% at 550 nm	Indophenol blue method	96
Ti_3C_2 -P25	$N_2/H_2O(l)$	None	Full spectrum	$10.74 \ \mu mol \ g^{-1}$	Not reported	Ion chromatography	103
Pt-Loaded ZnO	$N_2/H_2O(l)$	Na ₂ SO ₃	UV	860 mmol $g^{-1} h^{-1}$	Not reported	Indophenol blue method	104
SV-1T-MoS ₂ /CdS	$N_2/H_2O(l)$	Methanol	420–780 nm	8220.83 μ mol L ⁻¹ h ⁻¹ g ⁻¹	4.424% under simulated solar light	Nessler's reagent	105
NiS/CdS	$N_2/H_2O\left(l\right)$	None	Full spectrum	$2.8 \text{ mg L}^{-1} \text{ h}^{-1}$	0.76% at 420 nm	Nessler's reagent	106
Pt-SACs/CTF Ru/RuO ₂ /g-C ₃ N ₄	$\begin{array}{l} N_{2}/H_{2}O \left(l \right) \\ N_{2}/H_{2}O \left(l \right) \end{array}$	None Methanol	420–780 nm Full	171.4 μ mol g ⁻¹ h ⁻¹ 13.3 μ mol g ⁻¹ h ⁻¹	1.4% at 420 nm Not reported	Nessler's reagent Ion chromatography	107 108
Fe@graphene	N ₂ /H ₂ , 200 °C	None	200–600 nm	420 $\mu g g_{cat}^{-1} h^{-1}$	Not reported	Indophenol blue method	110
g-C ₃ N ₄ /Bi ₂ MoO ₆	$N_2/H_2O(l)$	Methanol	$\lambda > 420 \text{ nm}$	$3271 \ \mu mol \ L^{-1} \ g^{-1}$	Not reported	Nessler's reagent	111
TiO ₂ @C/g-C ₃ N ₄	$N_2/H_2O(l)$	Methanol	$\lambda > 420 \text{ nm}$	250.6 μ mol g ⁻¹ h ⁻¹	0.14% at 420 nm	Nessler's reagent	112
Bi2MoO6/OV-	$N_2/H_2O(l)$	None	Full	81.0 μ mol g ⁻¹ h ⁻¹	Not reported	Nessler's reagent	116
BiOBr			spectrum				

active N defect sites (-C \equiv N), which indicated that the introduction of the N-defect of -C \equiv N could significantly change

the optical properties. Fig. 5b displays the band structures of mCNN and pristine $g-C_3N_4$ through the results of experiments.

(cc)



Fig. 3 Schematic of the OV-induced enhanced interfacial electron transfer processes over BOB-001-OV. (b) Time-resolved photoluminescence (PL) spectra of BOB-001-OV and BOB-001-H. (c) The photocatalytic NH₃ production of BOB-001-OV and BOB-001-H under visible light ($\lambda > 420$ nm). Reproduced from ref. 31 with permission from ACS Publication.

Compared with pristine g-C₃N₄, a subgap state was presented for mCNN, which could be ascribed to the N defect, resulting in a broad visible-light response. The enhanced EPR intensity (Fig. 5c) of mCNN compared to pristine g-C₃N₄ was assigned to the strong electron withdrawing groups of $-C \equiv N$ on mCNN, which could delocalize the isolated electrons in mCNN, therefore promoting the separation of photocarriers and increasing the generation of active radical species to boost the activity of NH₃ photosynthesis. The rate of NH₃ generation of the mCNN photocatalyst was measured to be 3.42 mmol g^{-1} h⁻¹ with ethylene glycol as a scavenger under visible light irradiation (Fig. 5d), which was much higher than that of pristine $g-C_3N_4$ (1.11 mmol g^{-1} h^{-1}). The DFT calculations revealed that K⁺ could be linked to the unsaturated C centers by coordination as shown in Fig. 5e, which could adsorb N_2 as the lone-pair electrons of nitrogen would fill the empty state in K^+ (ΔG = -0.28 eV), followed by the rearrangement of K⁺ with the C atom and the adsorption of N₂ ($\Delta G = -0.17$ eV). Because of the large ion hydration free energy of K⁺, it could be extracted back into solution, then forming a C_2N_4 ring ($\Delta G = 1.64$ eV) intermediate which could undergo a MvK process to regenerate $-C \equiv N$, thereby stabilizing the unsaturated C sites.

Apart from the above NVs on the $g-C_3N_4$ photocatalyst, carbon vacancies (CVs) on a porous sulfur-doped $g-C_3N_4$ (SCNNSs) have also been exploited.⁵⁶ The introduction of CVs

was proved to play the same role as NVs, while the S-doping effect was demonstrated to improve the separation efficiency of photogenerated electron-hole pairs. Taking these advantages, the optimal SCNNSs showed an $\rm NH_3$ production rate of 5.99 mmol $\rm h^{-1}~g_{cat}^{-1}$.

Sulfur vacancies. Considering the importance of the sulfur element in nitrogenases, a few have reported the effects of sulfur vacancies (SVs) on N₂ photoreduction. It was reported that SVs could be created on the surface of $Mo_{0.1}Ni_{0.1}Cd_{0.8}S$ by co-doping Mo and Ni into CdS.⁵⁷ N₂-temperature-programmed desorption (N₂-TPD) results illustrated that the SVs on the surface of $Mo_{0.1}Ni_{0.1}Cd_{0.8}S$ obviously enhanced N₂ chemisorption (Fig. 6a), which was beneficial for NRR. Importantly, the photocatalytic NH₃ generation rate of $Mo_{0.1}Ni_{0.1}Cd_{0.8}S$ was linearly related to its SV concentration as shown in Fig. 6b. As the concentration of SVs increased, there was an increase in the photocatalytic NH₃ production rate. This result suggested that the SVs played a vital role in the photoreduction of N₂. The $Mo_{0.1}Ni_{0.1}Cd_{0.8}S$ with the highest SV concentration showed the highest NH₃ production rate of 3.2 mg h⁻¹ g_{cat}⁻¹ (Fig. 6b).

Doping. Metal doping is a very promising strategy to change the electronic structure and surface property of photocatalysts to enhance the photocatalytic activity.⁵⁸⁻⁶³ In one report,



Fig. 4 (a) Schematic representation of the layered LDH structure with defective MO_6 octahedra. (b) Schematic of the in-plane biaxial compressive strain in CuCr-NS. (c) The yield of NH_3 over different LDH photocatalysts under visible-light illumination ($\lambda > 400$ nm). Reproduced from ref. 34 with permission from Wiley-VCH.

Schrauzer et al. studied the effect of different metal doped TiO₂ on the photocatalytic activity of N₂ reduction, including iron (Fe), chromium (Cr), cobalt (Co), and molybdenum (Mo).¹⁷ They found that Fe doping was the most effective for enhancing the photocatalytic activity of TiO₂ for photosynthesis of NH₃ from N₂ and H₂O. However, O₂ production as the oxidation product was not reported. In this regard, Zhao et al. investigated the Fe-doped TiO_2 with highly exposed (101) facets for N_2 photofixation,⁶⁴ and found that an optimum Fe³⁺ doping content played a key role in inhibiting the recombination of photoinduced electron-hole pairs, which could act as a temporary electron/hole trapping sites, therefore enhancing the concentration of charge carriers and improving the photocatalytic performance. With this in mind, Liu et al. also reported a Fe-doped SrMoO₄ (FSMO) as a potential candidate for N_2 photoreduction.⁶⁵ Further studies revealed that the intrinsic bandgap of SrMoO₄ could be shrunk from 3.98 eV to 2.93 eV with the increase in Fe doping concentration (from 0 to 5.1%), resulting in the extension of light adsorption from the ultraviolet to the visible-light region. Besides that, the Fe doping could induce the formation of surface defects as active sites for N₂ adsorption and significantly retard the recombination of electrons and holes, leading to enhanced N2 reduction reaction. As a result of these properties, an improved NH₃ production rate of 93.1 μ mol g⁻¹ h⁻¹ over the optimal FSMO was achieved compared with that of pristine SrMoO₄ (66.7 μ mol g⁻¹ h⁻¹). In another related work incorporating Fe into BiOCl nanosheets, Fe-doped BiOCl nanosheets (BiOCl NSs-Fe) were developed for N₂ photoreduction.⁶⁶ The optimal BiOCl NSs-Fe exhibited a marked enhancement of photocatalytic NH3 production, and

the efficiency was 2.53 times higher than that of pristine BiOCl NSs.

In another study, Mo was successfully doped into W₁₈O₄₉ nanowires to produce Mo-doped W18O49 nanowires (MWO-1) as shown in Fig. 7a.⁶⁷ Compared with OV-rich W₁₈O₄₉ nanowires, Mo-doping had many kinds of effects on photocatalytic N₂ reduction. Fig. 7b displays the electronic band structures of MWO-1 and $W_{18}O_{49}$; it is observed that the defect-band center could be shifted to the Fermi level by Mo doping, which provided more energetic electrons for NRR. Theoretical simulations revealed that the Mo-W centers could alter electron distribution, leading to a larger adsorption energy (-2.48 eV)relative to W₁₈O₄₉ with W-W sites (1.65 eV), which was in favor of N₂ chemisorption and activation (Fig. 7c). Additionally, the enhanced M-O co-valence caused by Mo doping could effectively promote the electron transfer from metal active centers to adsorbed N₂ molecules. Thus, the optimal MWO-1 exhibited an excellent NH_3 yield rate of 195.5 µmol g^{-1} h^{-1} under fullspectrum irradiation (Fig. 7d), which was 7 times higher than that of W18O49, and also realized a high AQE of 0.33% at 400 nm.

Furthermore, Cu-doped ultrathin TiO₂ nanosheets (TiO₂-V_ostrain) were also studied.⁶⁸ Compared with pristine TiO₂, introducing Cu into TiO₂ could create abundant OVs and cause lattice distortion and strain effects, resulting in a significant increase of N₂ adsorption energy on the surface of TiO₂-V_ostrain (-0.37 eV) compared with that of pristine TiO₂ (-0.17 eV, Fig. 8a). The increased adsorption energy promoted the electron transfer from TiO₂ to N₂, thereby breaking the N \equiv N bonds. Meanwhile, the required reaction energy for N₂ hydrogenation to



Fig. 5 (a) UV-vis diffuse reflectance spectra (DRS). (b) Schematic illustration of energy band structures. (c) Room-temperature electron paramagnetic resonance (EPR) spectra. (d) NH₃ production rates of $g-C_3N_4$ and mCNN. (e) The calculated free-energy changes for the NRR pathway using mCNN. The blue sphere represents N, the grey sphere represents C, the white sphere represents H, and the purple sphere represents K⁺. Reproduced from ref. 55 with permission from Wiley-VCH.

N–NH* was only 0.365 eV on TiO₂-V_o-strain, which was lower than that on pristine TiO₂ (2.115 eV, Fig. 8b). As a result, the optimal TiO₂-V_o-strain (6% TiO₂) achieved an enhanced NH₃ yield rate of 78.9 µmol g⁻¹ h⁻¹ under full solar irradiation, about 5.2 times higher than that of the TiO₂ nanosheets with OVs (0% TiO₂, Fig. 8c). In addition, the yield rate of O₂ (59.1 µmol g⁻¹ h⁻¹) and NH₃ mentioned above over TiO₂-V_o-strain was close to the

stoichiometric ratio of 3:4, revealing that the protons in NH₃ were from the H₂O molecules. Most recently, a novel bimetallic system with Fe–Pt loaded g-C₃N₄ was used for efficient ammonia synthesis under mild conditions.⁷² Further investigations proposed that the doping of Pt onto the Fe nanocluster over the surface of g-C₃N₄ could cause an uplift of the energy band of semiconductors and form a large Schottky barrier, thus leading to an improved separation of photogenerated carriers and enhanced N₂ reduction. Accordingly, 0.3 wt% Pt doped on 3 wt% Fe@C₃N₄ exhibited a high NH₃ production rate of 63 μ g h⁻¹ g⁻¹ with gaseous H₂ and N₂ as reactants under visible light irradiation and the AQE was tested to be 0.15% between 450 and 500 nm.

Apart from metal doping, a metal-free B-doped g-C3N4 nanosheet (BCN) with exposed active N atoms was recently synthesized for highly efficient ammonia synthesis.⁷³ Theoretical studies revealed that the exposed N atoms could be stabilized by B-N-C coordination on BCN, which was different from that in the pristine g-C₃N₄. The B dopants were proved as active sites for N2 adsorption and activation and could effectively retard charge recombination and improve light utilization. The optimal BCN with 13.8 wt% B-dopants exhibited a remarkable NH₃ yield rate of 313.9 μ mol g⁻¹ h⁻¹ under visible light irradiation in the presence of Na₂SO₃ as a hole scavenger, which was much higher than that (32.8 μ mol g⁻¹ h⁻¹) over pristine g-C₃N₄ and also achieved a good QE of around 0.64% at 420 nm. In addition, carbon-doped TiO2 was also reported for N₂ photoreduction, which exhibited an NH₃ yield rate of 109.3 μ mol g⁻¹ h⁻¹.

Morphology engineering

Facets. Since the surface atomic distribution has a huge effect on the active sites and electronic structures of photocatalysts,^{69,74–76} many researchers attempted to control the crystal facet of semiconductors to enhance the photocatalytic N₂ reduction. For instance, two Bi₅O₇I nanosheets with different {100} and {001} facets were synthesized successfully *via* hydrolysis and calcination methods, respectively.⁷⁷ Further investigations



Fig. 6 (a) The N_2 -TPD of $Mo_{0.1}Ni_{0.1}Cd_{0.8}S$ and $Mo_{0.1}Ni_{0.1}Cd_{0.8}S$. (b) The relationship of NH_3 yield over the obtained photocatalysts and the SV concentration. Reproduced from ref. 57 with permission from The Royal Society of Chemistry.



Fig. 7 (a) The scanning TEM (STEM) image and the corresponding elemental mapping of MWO-1. (b) Schematic illustration of the band structures of $W_{18}O_{49}$ and MWO-1. (c) Schematic simulation for N_2 adsorption and activation on the surface active sites of the Mo-doped $W_{18}O_{49}$ model. (d) The photocatalytic NH₃ yield on various catalysts. Reproduced from ref. 67 with permission from ACS Publication.

revealed that Bi_5O_7I -001 had more negative conduction band position (-1.45 eV) compared with that in Bi_5O_7I -100 (-0.85 eV) and exhibited higher efficiency for separation of photoinduced carriers, thus leading to a high photocatalytic activity for N₂ photoreduction. Accordingly, a remarkable NH₃ generation rate of 111.5 µmol g⁻¹ h⁻¹ over Bi_5O_7I -001 was achieved using methanol as a hole scavenger and the AQE of that was increased to 5.1%.

In another report, Zhang et al. also systematically investigated the influence of {001} and {010} facets of OV-rich BiOCl nanosheets on N₂ adsorption and activation.⁷⁸ Experimental results showed that {010} facet BiOCl nanosheets (BOC-010) exhibited a superior performance with a NH₃ yield of 4.62 μ mol g⁻¹ h⁻¹, which was around 2.5 times higher than that on {001} facet BiOCl nanosheets (BOC-001, Fig. 9a). Meanwhile, it was observed that N₂H₄ which served as a main intermediate was accumulated on BOC-010 during N2 photoreduction reaction within 30 min and was consumed gradually to be converted into NH₃ (Fig. 9b). Importantly, when N₂H₄ was used as the reactant, both BOC-010 and BOC-001 showed a similar photocatalytic conversion efficiency of N₂H₄ under simulated solar irradiation (Fig. 9c), which in turn meant that BOC-010 had a stronger ability to generate N2H4 intermediates. Further DFT calculations revealed that the N_2 fixation on BOC-010 followed an alternative pathway with N2H4 as the main intermediate, which could provide a lower energy pathway for N₂ fixation *via* proton-coupled electron transfer compared with that *via* a distal pathway occurring on BOC-001 facets, thus resulting in enhanced NH_3 production (Fig. 9d and e).

Nanostructure engineering. Nanomaterials have preternatural interface structures and unique functions, such as the small size effect, the surface and boundary effect, quantum size and so on.⁷⁹⁻⁸⁵ In order to increase the catalytic active sites of the photocatalytic reduction of N2, Sun et al. synthesized BiO quantum dots with an average size of 2-5 nm (Fig. 10a), which showed an NH₃ production rate of 1226 μ mol g⁻¹ h⁻¹ without a cocatalyst and a sacrificial agent.⁸⁶ Meanwhile, the amount of produced O₂ increased continuously with increasing irradiation time, consistent with the stoichiometric chemistry. Kinetic analysis and quantum chemical calculations suggested that the highly efficient photocatalytic activity of BiO quantum dots could be attributed to the fact that the smaller size endowed the surface and edge of BiO rich in Bi²⁺ species, which had the potential to increase the electron donation to the anti-bonding π^* orbitals of N₂, thereby could act as active sites to adsorb and activate N₂ (Fig. 10b). More recently, a tubular OV-rich Bi₅O₇Br (Bi₅O₇Br-NT) with a diameter of 5 nm (Fig. 10c) was prepared and it exhibited a maximum NH₃ yield rate of 1.38 mmol g^{-1} h⁻¹ (Fig. 10d) upon changing the OV concentration.87 A high specific surface area of up to 96.56 m² g⁻¹ was observed for Bi₅O₇Br-NT, which indicated the exposure of abundant surface



Fig. 8 (a) The N_2 adsorption energies by DFT calculations on different photocatalysts. (b) The calculated Gibbs free energy for N_2 reduction on the (001) surface of different photocatalysts (H: white sphere, Ti: gray sphere, N: blue sphere, O: red sphere). (c) Yield of NH_3 over various samples under UV-vis irradiation. Reproduced from ref. 68 with permission from Wiley-VCH.

OVs for the chemisorption and activation of N₂. It was found that the OVs on the Bi5O7Br-NT surface could not only effectively promote N₂ adsorption and activation, but also could be regenerated by capturing O atoms from H₂O after the reaction to maintain the good stability of Bi5O7Br nanostructures. As a result, the calculated AQE for the Bi5O7Br-NT photocatalyst was 2.3% under visible light irradiation at 420 nm (Fig. 10e). Furthermore, it was reported that metal-free black phosphorus nanoflakes with abundant edges (eBP NFs) synthesized via a facile chemical etching exfoliation method exhibited a remarkable NH₃ yield rate of 2.37 mmol $g^{-1} h^{-1}$ under visible light irradiation in the presence of Na2SO3 and Na2S·9H2O as scavengers.⁸⁸ The photoelectrochemical characteristics (PEC) and transient absorption (TA) studies revealed that the efficient ammonia synthesis was attributed to rich edges on the surface, which could provide abundant active sites for enhanced N₂ adsorption and activation. Similarly, a nanocomposite (SiO₂/C-RP) prepared by loading red phosphorus on SiO₂ nanospheres showed superior charge separation.⁸⁹ Besides, this hybrid nanostructure exhibited a large surface area, good water dispersibility and large light adsorption. As a result of these benefits, SiO₂/C-RP exhibited an NH₃ production yield of $0.73 \ \mu mol \ h^{-1}$ under full-spectrum irradiation.

Interfacial modulation

Cocatalyst loading. With the similar idea of using metal cocatalysts to inhibit the recombination of electrons and holes

and enhance the photostability of catalysts in other photocatalytic processes, e.g. water splitting,⁹⁰⁻¹⁰² Ranjit et al. studied different metal loaded TiO₂ toward the photoreduction of N₂, including ruthenium (Ru), rhodium (Rh), palladium (Pd), and platinum (Pt).93 It was found that the order of the photocatalytic activity of these metals on TiO_2 was Ru > Rh > Pd > Pt. The excellent performance of Ru-loaded TiO2 could be assigned to the high metal-hydrogen bond strength which well correlated with the high production of NH₃. In recent years, singleatom catalysts (SACs) have been well studied as excellent candidates for boosting the catalytic activity and improving the utilization efficiency of metal atoms during the photocatalytic process.94 To further improve the performance of the photocatalytic NH₃ synthesis, a single atomic Ru decorated TiO₂ nanosheet with abundant OVs was prepared.95 The DFT calculations indicated that the single atomic Ru species were favorable to be formed and dispersed on the OVs over the TiO₂ nanosheet surface. Further investigations revealed that the isolated Ru atom could serve as the active site for N2 adsorption and activation, promote the separation of photogenerated charge carriers efficiently, as well as inhibit the competitive H₂ evolution reaction, thus leading to an improved NH₃ photosynthesis. Thus, a 1 wt% single Ru atom decorated TiO2 nanosheet exhibited a superior performance with an NH₃ yield of 56.3 μ g h⁻¹ g_{cat}⁻¹, which was two times as high as that of pure TiO2. Recently, Au-anchored TiO2 nanosheets with OV (Au/TiO2-OV) photocatalysts were developed for N₂ photofixation.⁹⁶ As shown in Fig. 11a, Au nanospheres



Fig. 9 Photocatalytic performance for N₂ reduction on BOC-001 and BOC-010. The yield comparison of produced (a) NH₃ and (b) N₂H₄ on BOC-001 and BOC-010 under simulated solar light irradiation. (c) The NH₃ yield produced from N₂H₄ BOC-001 and BOC-010 under simulated solar light irradiation. The calculated free energy change for N₂ reduction (d) on the (001) surface via a distal pathway and (e) on the (010) surface via an alternating pathway. Reproduced from ref. 78 with permission from The Royal Society of Chemistry.



Fig. 10 (a) TEM image of BiO quantum dots. (b) Proposed mechanism for N₂ photoreduction on BiO quantum dots. Reproduced from ref. 86 with permission from The Royal Society of Chemistry. (c) TEM image of Bi₅O₇Br-NT. (d) Yield of NH₃ for Bi₅O₇Br-NT. (e) The wavelength-dependent AQE of Bi₅O₇Br-NT. Reproduced from ref. 87 with permission from Wiley-VCH.

with a diameter of 20 nm \pm 1.4 nm were uniformly distributed

Au/TiO2-OV showed absorption characteristics of Au loaded on the surface of TiO₂-OV nanosheets. The UV-vis spectrum of TiO₂ (Au/TiO₂) and TiO₂-OV, displaying a broad localized surface plasmon resonance (LSPR) peak at 550 nm and an obvious absorption tail (Fig. 11b). Therefore, in the Au/TiO₂-OV hybrid, OVs on the surface of TiO₂ nanosheets chemisorbed and activated N₂ molecules, which were reduced to NH₃ by plasmon-induced hot electrons from Au nanoparticles in the presence of methanol as a hole scavenger (Fig. 11c). As a result, the optimal Au/TiO₂-OV exhibited an NH₃ photoproduction rate of 78.6 µmol g⁻¹ h⁻¹, which was 98 and 35 times higher than that of Au/TiO₂ and TiO₂-OV respectively (Fig. 11d). Recently, we reported a hybrid of 2D layered Ti₃C₂ and P25 TiO₂ (Ti₃C₂-P25), in which Ti₃C₂ served as the cocatalyst to facilitate charge separation due to its excellent electrical conductivity. The DFT calculation (Fig. 11e) revealed that the N₂ adsorption energies were ranked as Ti₃C₂ (2.731 eV) > VOS-TiO₂ (0.342 eV) > TiO₂

(0.170 eV), implying that Ti_3C_2 had a much stronger N_2 chemisorption effect compared with VOs-TiO₂ and TiO₂. Therefore the introduction of Ti_3C_2 on P25 could accelerate N_2 chemisorption, leading to five times higher photocatalytic yield of NH₃ than that on pure P25. More importantly, water acted as the electron donor in this study and stoichiometric O₂ production was also observed, which was one of a few examples that could observe the stoichiometric reduction and oxidation products.¹⁰³

In addition to TiO₂-based photocatalysts, Pt-loaded ZnO was reported as an efficient photocatalyst for N₂ photoreduction which exhibited an NH₃ yield rate of 860 mmol g⁻¹ h⁻¹.¹⁰⁴ More recently, O-doped 1T-MoS₂ nanosheets with a large amount of SVs (SV-1T-MoS₂) were used as cocatalysts over CdS nanorods for



Fig. 11 (a) TEM image of Au/TiO₂-OV. (b) Adsorption spectra of different photocatalysts. (c) The proposed schematic for photocatalytic N_2 reduction over the Au/TiO₂-OV catalyst under visible-light irradiation. (d) Photocatalytic N_3 production with different photocatalysts under visible light irradiation. Reproduced from ref. 96 with permission from ACS Publication. (e) Schematic of the adsorption structure on TiO₂ (A), OVs-TiO₂ (B) and Ti₃C₂ MXenes (C). Reproduced from ref. 103 with permission from Elsevier Publication. (f) Schematic for photocatalytic N_2 reduction over Fe@graphene photocatalysts. Reproduced from ref. 108 with permission from ACS Publication.

photocatalytic N₂ reduction.¹⁰⁵ The DFT calculations revealed that the SVs and the metal properties of 1T-MoS₂ could effectively promote the separation of h^+/e^- and the presence of SV-1T-MoS₂ could also provide abundant active sites, resulting in enhanced N₂ adsorption and immobilization. Accordingly, a remarkable performance over the optimal SV-1T-MoS₂/CdS was realized with a superior NH₃ yield rate of 8220.83 μ mol L⁻¹ h⁻¹ g⁻¹ under simulated solar light irradiation. Besides, NiS was also studied as a cocatalyst over CdS nanorods for ammonia photosynthesis.¹⁰⁶ The DFT calculation indicated that the NiS cocatalyst could reduce the adsorption energy of N₂ from 1.16 eV on the CdS surface to -0.55 eV on the Ni-doped CdS surface. Further characterization revealed that charge separation could also be enhanced by loading NiS on the CdS surface. Because of these properties, a favorable NH₃ yield of 2.8 mg L^{-1} was reported within the first hour in pure water under fullspectrum irradiation. Recently, single-atom Pt modified triazine framework (CTF) nanosheets (Pt-SACs/CTF) were developed for photocatalytic NH₃ production.¹⁰⁷ It was found that the Pt-N₃ sites were formed in Pt-SACs/CTF, leading to more negative conduction band position with accelerated thermodynamics and fast interfacial charge migration ability, and therefore a high NH₃ production rate of 171.4 μ mol g⁻¹ h⁻¹ under visible light irradiation. Most recently, we synthesized a ternary Ru/RuO₂/g-C₃N₄ system for N₂ photoreduction, which exhibited a photocatalytic NH₃ yield of 13.3 μ mol g⁻¹ h⁻¹ whilst no NH₃ could be measured for pure g-C₃N₄ under the same condition. Such significant improvement in photocatalytic NH₃ synthesis for Ru/RuO₂/g-C₃N₄ was not only because of Ru and RuO₂ acting as cocatalysts to promote electron and hole transfer respectively, but also due to the advantage of Ru for N₂

chemisorption and activation.¹⁰⁸ Besides that, carbon-based materials especially graphene are also often used as cocatalysts to prevent the photoinduced electron–hole recombination and promote the electron transfer due to their prominent electrical conductivity.^{109,110} For instance, a Fe modified three-dimensional graphene (Fe@graphene) photocatalyst was reported for NH₃ production.¹¹⁰ In the Fe@graphene system (Fig. 11f), graphene generated hot electrons under light irradiation and transferred those electrons to Fe, while Fe acted as an electron sink and provided the catalytic active sites for the adsorption and activation of N₂.

Junction structure. The combination of two semiconductors as a photocatalyst would overcome the shortages of each component, and construct the heterostructure or Z-scheme system with improved photoelectric properties for broad applications.^{111–115} In one work, Bi₂MoO₆ was implanted on g-C₃N₄ nanosheets to enhance the photocatalytic N₂ reduction.¹¹¹ In this case, the obtained g-C₃N₄/Bi₂MoO₆ heterojunction showed effective separation of charge carriers and enhanced photocatalytic performance for NH₃ production. In another report, MXene-derived TiO₂(@C incorporated with g-C₃N₄ (TiO₂(@C/ g-C₃N₄, Fig. 12a) was prepared for efficient NH₃ photocatalysis.¹¹² Compared with the pristine g-C₃N₄, TiO₂@C/g-C₃N₄ showed a significantly decreased PL intensity (Fig. 12b), which indicated that the heterostructure promoted the charge transfer, which in turn inhibited the recombination of photoinduced electronhole pairs. Furthermore, the transient photocurrent density of TiO₂(C/g-C₃N₄ was about 1.7 times higher than that of g-C₃N₄ (Fig. 12c), suggesting the improved separation efficiency of the charge carriers. The N_2 -TDP result revealed that the Ti³⁺ species on TiO₂ and carbonaceous components were responsible



Fig. 12 (a) SEM image of TiO₂@C/g-C₃N₄. (b) PL spectra of TiO₂@C/g-C₃N₄ and g-C₃N₄. (c) Transient photocurrent responses of TiO₂@C/g-C₃N₄ and g-C₃N₄. (d) The N₂-TPD profiles. (e) The yield of produced NH₃ under visible light irradiation ($\lambda > 420$ nm). Reproduced from ref. 112 with permission from The Royal Society of Chemistry.

for the adsorption and activation of N2 in TiO2@C/g-C3N4 (Fig. 12d). As a result, a superior performance over the optimal TiO₂(@C/g-C₃N₄:10 (10 represents the molar ratio of starting materials of melamine/Ti₃C₂) was realized with an NH₃ production yield of 250.6 μ mol g⁻¹ h⁻¹ using methanol as a scavenger under visible light irradiation (Fig. 12e). Recently, a p-n junction of Bi2MoO6/OV-BiOBr combining n-type Bi2MoO6 nanorods with OVrich p-type BiOBr nanosheets displayed efficient charge separation and a broad range of light absorption.¹¹⁶ Moreover, OVs on the surface of Bi₂MoO₆/OV-BiOBr were beneficial for the chemisorption and activation of N2, and the nanosheet morphology could provide a large specific surface area with more active sites for photoreduction of N2. Benefiting from these advantages, the optimal Bi2MoO6/OV-BiOBr exhibited a photocatalytic yield of NH₃ of 81.0 μ mol g⁻¹ h⁻¹ under visible light illumination in pure water, and no O₂ production was reported here.

Conclusion and perspectives

The photosynthesis of NH_3 is an energy-saving process and has high potential for substantial contribution to economic and social sustainability. Compared with the traditional Haber– Bosch process and the emerging electrochemical process, photocatalytic NH_3 synthesis exhibits very low efficiency, mostly at micromoles $g^{-1} h^{-1}$ if using water as the electron donor, and thus is far from practical application. However as photocatalysis can be driven by abundant solar energy, it is a carbon-free process. Besides, it requires a solar energy input of 208.3 MJ kg⁻¹-NH₃ compared with that of 339.1 MJ kg⁻¹-NH₃ in the electrochemical process.¹¹⁷ Thus, it has strong potential to achieve NH_3 synthesis with affordable costs in particular taking into account the sustainability and the trend of decarbonatization in the industry. However there is a long way to go in order to realize this potential.

This review does not detail different photocatalysts as there are a few reviews on them, but analyses surface engineering and interface engineering in photocatalysts developed recently for the photocatalytic NH_3 synthesis, involving oxygen vacancies, nitrogen vacancies, carbon vacancies, sulfur vacancies, metal and non-metal doping, facet modulation, nanostructure engineering, and heterostructure construction such as loading with cocatalysts and modification with other semiconductors, together with the mechanism of N_2 reduction reaction and the reliable means for the detection of NH_3 .

Great progress has been made in the study of photoreduction of N_2 to NH_3 as briefed in Fig. 13, but there are still many problems, some of which are very critical. First, the majority of the studies so far reported use an efficient and expensive hole scavenger to get long lived photoelectrons for N_2 reduction. However, a practical pathway should use water as the only electron donor and to provide protons for the photosynthesis of NH_3 , as such NH_3 synthesis by photocatalysis is scientifically meaningful and economically sustainable. The slow progress linked to this profile is mainly due to the very limited understanding in this field. Second, there are few reports specifying



Fig. 13 Current work and future challenges highlighted in this review.

the stoichiometric chemistry in the photochemical process. Without the stoichiometric O_2 gas produced, such N_2 reduction to NH_3 is questionable. Furthermore, as O_2 could be leaked from air, the isotopic measurement of O_2 production is necessary. In addition, since H_2 production would compete with NH_3 synthesis, a comprehensive study should detail the selectivity between the two products and discuss the strategy to favor NH_3 synthesis. In addition an experimental error bar is very crucial for such NH_3 synthesis in order to improve the confidence as almost all studies were carried out in a batch reactor with quite a small amount of NH_3 produced, which was quite easy to be interfered by occasional factors.

Apart from the issues mentioned above, photocatalytic NH_3 synthesis also faces a few tough challenges. The majority of the studies show that the NH_4 amount produced is less than 10 µmol h⁻¹ (instead of the unit of µmol g⁻¹ h⁻¹) when using water as the electron donor and 10 times enhancement is achieved when using an organic hole scavenger. This amount is lower than the NH_3 amount in the river water which is about 0.01 mM.¹¹⁸ Besides, since the NH_3 yield is extremely easy to be interfered by environmental impurities and different detection agents, it is difficult to obtain reliable and reproducible results by just one analysis method.¹¹⁹ At least two methods have to be applied to prove the consistent results and to improve the reproducibility of the process.

The surface states of a catalyst can dominate its performance, such as surface defects. However, to quantify the correlation of the surface defects with the catalytic activity is very challenging at present. This should be undertaken in the future in order to distinctly guide catalyst surface state control. Furthermore the cocatalyst is another key factor to control both charge separation and catalytic performance. The majority of the cocatalysts reported are either large particles or nanosized particles. Single atomic catalysis is an emerging area, which

presents unprecedented activity in some chemical processes. Such unique reaction sites should be introduced to ammonia synthesis with in-depth exploration of their intrinsic function. In addition, a junction structure is widely accepted to help charge separation, which was also reviewed in the previous session. The new design strategy should be applied to construct new junctions, such as polymer and oxide junctions as the former has likely better N₂ adsorption due to the potential hydrogen bond between the organic polymer and N₂ while the latter has a very positive VB for water oxidation.

The modified catalyst discovery is very informative. Equally, the mechanism and reaction pathways for photocatalytic N_2 fixation are scarce and much less investigated, forming an obstacle for the rational design of highly efficient photocatalysts. Currently, most of the given reaction mechanisms and reaction pathways were based on assumptions and lacked solid evidence. Thus, the current catalyst development is more or less a try-and-error process. Some advanced operando technologies in functional characterization should be applied to comprehensively study the reaction pathway such as by time resolved spectroscopy to investigate charge carrier dynamics, and by transient and stationary spectroscopy to observe the reaction intermediates.

In addition, it is of paramount importance to design a flow reaction system for N2 photoreduction. The current reaction system is composed of a batch reactor, which is far from the requirement of the industry. The typical batch reactor is easy to be constructed; however, its efficiency is severely restricted by the low mass transfer between N2 gas and aqueous solution due to the low solubility of N2, thereby resulting in a low photocatalytic efficiency. Besides, NH3 accumulated in the batch reactor during the reaction process will be overoxidized to other byproducts, thereby resulting in a low conversion rate and even bad selectivity. Moreover, based on the industrial viewpoint, it is quite costly to separate the photocatalysts from reactants and products in a batch system. Thus, an intensified flow reactor such as using N2 and water vapor as reactants should be explored to overcome these drawbacks and to meet the industrial requirement in the future, underlining the crucial collaborations between chemical scientists and experts in reaction engineering.

Last, modelling will be expected to combine with experimental results to figure out the reaction mechanism and speed up the rational design of highly efficient photocatalysts. Meanwhile, the big data, together with artificial intelligence (AI) and machine learning (ML), will be a future key research area to improve the reproducibility of the catalyst synthesis, to facilitate catalyst screening, to enhance the experimental safety and to save the experimental costs and time.

Overall, this research field is at an infant state and all these areas should be enhanced in order to improve the NH₃ synthesis rate with high reproducibility and reliability of the procedure.

Conflicts of interest

There are no conflicts to declare.

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