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Impact of nitrogen doping on triazole-based graphitic carbon Nitride-TiO₂ (P25) S-scheme heterojunction for improved photocatalytic hydrogen production†

Saravanan Kamalakannan,^a Natarajan Balasubramaniyan,^{ID} ^{*a}
Neppolian Bernaudshaw^b and Ganesh Vattikondala^c

Establishing an S-scheme heterojunction is a promising method for increasing the photocatalytic activity of synthetic materials. In this study, nitrogen-doped g-C₃N₅/TiO₂ S-scheme photocatalysts have been synthesized and examined for photocatalytic hydrogen production using thermal decomposition methods. Nitrogen-doped g-C₃N₅/TiO₂ composites performed better than pure nitrogen-doped g-C₃N₅ and TiO₂ alone. Using experiments and density functional theory (DFT) calculations, nitrogen (N) doping was identified as being introduced by replacing the carbon (C) atoms in the matrix of g-C₃N₅. In addition to its narrow band gap, N-doped g-C₃N₅ showed efficient carrier separation and charge transfer, resulting in the enhanced absorption of visible light and photocatalytic activity. DFT, XPS, optical property characteristics, and PL spectra confirmed these findings, which were attributed to the successful nitrogen doping, and the composite was proven to be a potential candidate for photocatalytic hydrogen generation under light irradiation. The quantity of H₂ produced from the nitrogen-doped g-C₃N₅/TiO₂ composite for 3 hours (3515.1 μmol g⁻¹) was about three times that of N-doped g-C₃N₅. The H₂ production percentage of the nitrogen-doped g-C₃N₅/TiO₂ catalyst with Pt as the cocatalyst was improved by nearly ten times as compared to N-doped g-C₃N₅/TiO₂ without a cocatalyst. Herein, we report the successful preparation of the N-doped g-C₃N₅/TiO₂ S-scheme heterojunction and highlight a simple and efficient catalyst for energy storage requirements and environmental monitoring.

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1. Introduction

Researchers are interested in graphitic carbon nitride (CN) due to its exclusive properties, such as its non-metallic nature, thermal stability, chemical stability, governable semi-conducting properties with the band gap energy of approximately 2.72 eV, small charge, ease of research, and eco-friendliness.^{1,2} CN materials with C/N ratios ranging from 0.4 to 3 have been designated as C₃N₇, C₃N₆, C₃N₅, C₃N₄, C₃N₃, C₃N₂, C₃N, and so on. C₃N_x (x = 1–7) materials with various C/N ratios have been reported, with g-C₃N₄ being the most researched

form of CN and receiving much attention over the past 20 years.^{3,4} As a lone pair electron donor, N can enhance charge transfer and thus activate the photocatalytic performance; the sp²-hybridized C and N for the triazine rings of g-C₃N₄ and the production of its C/N ratio play a vital role in the photocatalytic activity.⁵ To the best of our knowledge, adding nitrogen to the carbon matrix of CNs results in a narrow band gap. It improves the field emission, photocatalysis, fundamental catalysis, carbon capture, electrical characteristics, and hydrogen production.^{6,7} The primary focus of current research on CNs is the synthesis and description of their polymorphs. Unfortunately, these shapeless CN materials have limited long-term applications despite their exceptional nonporousness and small surface area.⁸ In general, the H₂ generation rate during photocatalysis is insufficient for the light absorption capacity and poor quantum efficiency imposed by the charge carrier lifetime and low surface area.^{9,10} As a result, enormous efforts were made to develop more reasonable model schemes suitable for visible-light photocatalysis.¹¹ Recently, several photocatalysts with various shapes and structures have been considered and synthesized. Due to its appropriate band size, physicochemical consistency, and other properties, the metal

^aDepartment of Chemistry, SRM Institute of Science and Technology, Kattankulathur – 603 203, Tamil Nadu, India. E-mail: natarajb@srmist.edu.in

^bDepartment of Chemistry, SRM Institute of Science and Technology, Kattankulathur 603 203, Tamil Nadu, India

^cDepartment of Physics and Nanotechnology, SRM Institute of Science and Technology, Kattankulathur, 603203, Tamil Nadu, India

† Electronic supplementary information (ESI) available: XRD patterns, FT-IR spectra, TEM images, XPS survey spectrum of NCN, TiO₂, and NCNT₅ samples, pristine g-CN (g-C₃N₅), UV-vis spectra of g-C₃N₄, g-CN (g-C₃N₅), NCN (nitrogen-doped g-C₃N₅), and density functional theory (DFT) calculations. See DOI: <https://doi.org/10.1039/d3na00597f>



oxide semiconductor has attracted significant attention for photocatalytic hydrogen production.¹² Recently, alternate N-rich precursors, such as melamine, thiourea and urea have been used to expand the photocatalytic performance of CN materials. It is, therefore, critical to investigate N-rich CN materials with a unique low band gap and structure to improve photocatalytic performance. Varied forbidden gap energies and rapid recombination ratios of visible-light photo-induced (e^-/h^+) during photoexcitation have limited the photoactivity of generally considered photocatalyst materials such as SnO_2 , WO_3 , ZnO , and TiO_2 .^{13,14}

Recently, a high (N ratio) polymer CN material of C_3N_5 was reported for its excellent photocatalytic H_2 and organic pollutant degradation with a shorter band gap (2.20 eV) and larger conductive band CB potential (1.47 V) than the popular $\text{g-C}_3\text{N}_4$. However, as with other semiconductors, the consumption of photo-generated carriers by internal recombination limits its applications. Intriguingly, the band gap of $\text{g-C}_3\text{N}_5$ can be tuned between 1.7 and 2.0 eV to increase the visible-light reactive photocatalytic energies, which are smaller than that of $\text{g-C}_3\text{N}_4$ (2.7 eV).^{15–17} Regarding structural engineering, many studies have found that $\text{g-C}_3\text{N}_4$ and $\text{g-C}_3\text{N}_5$, mesoporous construction, rod, and nanosheet-like formations have photocatalytic potential. The new material with a high N content has an extensive band gap range.¹⁸ Though the prepared $\text{g-C}_3\text{N}_5$ outperforms some previously reported $\text{g-C}_3\text{N}_4$, the heavy templating process for preparing $\text{g-C}_3\text{N}_5$ is expensive and time-consuming. CeTi_2O_6 ,¹⁹ a titanate photocatalyst material with a short band gap value of 2.73 eV, has been demonstrated to be advantageous in aggressive ionic conductors and semiconductor photocatalysts.^{20,21} TiO_2 is the most commonly used photocatalyst in photocatalytic processes, and the application study shows its efficacy in photocatalytic hydrogen production. Essential aspects of this phenomenon include its low activity and broad band gap (3.24 eV) and its recyclability under light due to the high probability of photo-induced (e^-/h^+) recombination.

To prepare N-doped $\text{g-C}_3\text{N}_5/\text{TiO}_2$ S-scheme heterojunction catalysts, we used a one-step polymerization route with citric acid, 3-amino-1,2,4-triazole (3-AT), and TiO_2 (P25) as initial products this work.^{22,23} Compared to $\text{g-C}_3\text{N}_5$ and TiO_2 (P25), a photocatalyst with a direct S-scheme heterojunction and an improved structure in N-doped $\text{g-C}_3\text{N}_5/\text{TiO}_2$, they exhibited increased interaction and toughness in visible light photocatalytic hydrogen production. Through three carboxyl groups, citric acid, a weak organic acid, remains among the most used predecessors in dehydration and carbonization reactions.^{24,25} Because of its excellent properties and significant assets,²⁶ nitrogen N doping has attracted increasing interest. Advantages of N-doping include: (1) $\text{g-C}_3\text{N}_5$ electronic band structure regulation, (2) avoiding the drawbacks of foreign atom introduction, (3) $\text{g-C}_3\text{N}_5$ aromatic pi-conjugated system extended and delocalized,^{27,28} (4) causing bordering carbon atoms to act equally as electron acceptors and electron donors. Nevertheless, N-doping of C_3N_5 is rarely used in photocatalytic hydrogen production applications.^{29–31} This paper investigates the photocatalytic activity of N-doped $\text{g-C}_3\text{N}_5/\text{TiO}_2$ for hydrogen production. The chemical structure, optical absorption, shape,

doping structure, and charge division have all been thoroughly investigated.³² Because of the introduction of the N element, N-doped $\text{g-C}_3\text{N}_5$ has a slight band gap and efficient charge separation.³³ Under visible light, the obtained composites demonstrated significantly improved photocatalytic efficiency for hydrogen evolution by H_2O splitting.^{34,35}

To the best of our knowledge, no extensive study has been directed toward preparing N-doped $\text{g-C}_3\text{N}_5/\text{TiO}_2$ S-scheme heterojunction composites and their application in photocatalytic hydrogen production. The photocatalytic appearances of the NCN/TiO_2 obtained were significantly improved. This study's N-doped triazole-based $\text{g-C}_3\text{N}_5$ opens the door to the growth of a novel CN-based material for photocatalytic hydrogen production with a wide range of applications. In this study, N-doped $\text{g-C}_3\text{N}_5$ (NCN) with nitrogen doping demonstrated significantly higher photocatalytic activity than new $\text{g-C}_3\text{N}_5$. When elemental nitrogen was added to $\text{g-C}_3\text{N}_5$, its increasing light absorption capacity resulted in many more photosensitive charge carriers. Additionally, surface impurities aided in the separation of (e^-/h^+) pairs. Exciting new materials could be achieved with n-doping and S-scheme heterojunctions to produce NCN/TiO_2 photocatalysts. As a result, developing an N-doped $\text{g-C}_3\text{N}_5$ sheet structure using a single-pot method was significant. We hope that the novel class of N-doped $\text{g-C}_3\text{N}_5/\text{TiO}_2$ composite nanomaterials are among the best candidates in hydrogen production applications.

Herein, we synthesized N-doped $\text{g-C}_3\text{N}_5/\text{TiO}_2$ nanocomposites using a citric acid monohydrate and 3-amino-1,2,4-triazole (3-AT) to prepare a series of $\text{g-C}_3\text{N}_5/\text{TiO}_2$ photocatalysts with N doping and evaluated the performance of photocatalytic H_2 production. 3-AT decomposed at high temperatures to yield cyanamide and hydrazoic acid, which also reacted with citric acid to produce a carbon nitride monomer containing two triazines and one triazole unit. Then, the N-doped triazole-based $\text{g-C}_3\text{N}_5/\text{TiO}_2$ was synthesized *via* a polycondensation reaction with the elimination of NH_3 at 550 °C. Scheme 1 represents the formation of an N-doped triazole-based $\text{g-C}_3\text{N}_5/\text{TiO}_2$ S-scheme heterojunction using citric acid monohydrate, TiO_2 (P25), and 3-AT as precursors.

2. Experimental section

2.1. Synthesis of bulk $\text{g-C}_3\text{N}_5$

The bulk $\text{g-C}_3\text{N}_5$ nanosheet was derived as follows: 5 grams of 3-amino-1,2,4-triazole was ground and then heated to (550 °C) for 3 hours at a ramp rate of 5 °C per minute. After subsequent cooling, the product was obtained and ground for characterization and applications. Comparatively, $\text{g-C}_3\text{N}_4$ was prepared through two sessions of calcination at 550 °C for three hours with intermediate grinding using melamine as the starting material. The triazole-based $\text{g-C}_3\text{N}_5$ produced only by 3-AT was designated as g-CN .

2.2. Synthesis of nitrogen-doped $\text{g-C}_3\text{N}_5$

A mixture of 5 grams of 3-amino-1,2,4-triazole (3-AT) powder and 5 mg of citric acid monohydrate was ground, then heated to





Scheme 1 The construction of the NCNT_x S-scheme heterojunction photocatalyst.

550 °C for 3 hours at a ramp rate of 5 °C min⁻¹. After cooling, the N-doped g-C₃N₅ was washed several times with deionized water and ethanol before being used for further experiments. NCN denotes the nitrogen-doped g-C₃N₅ produced by 3-AT and citric acid alone.

2.3. Preparation of nitrogen-doped g-C₃N₅/TiO₂ heterostructures

The following is a description of the NCN/TiO₂ formation process. The S-scheme heterojunction photocatalysts were prepared by dissolving variable amounts of 3-amino-1,2,4-triazole (3-AT) precursor (1, 2, 3, 4, and 5 g) and 5 mg of citric acid monohydrate in 50 mL of (DI) water to form a solution. A suspension was then formed by adding 0.2 g of TiO₂ (P25) to the solution with stirring. The suspensions were stirred for 2 hours before being dried by evaporation at 100 °C. To obtain the final NCN/TiO₂ composites, the samples were calcined at 550 °C for 3 hours at 5 °C min⁻¹. The products designated NCNT₁, NCNT₂, NCNT₃, NCNT₄, and NCNT₅.

2.4. Photocatalytic H₂-production

The photocatalytic H₂ production reaction was conducted in direct sunlight on the terrace of the SRM IST main block in the Kattankulathur Campus, Tamil Nadu, India. Here, 5 milligrams of composite catalyst was added to 50 mL of 5 volumes of aqueous triethanolamine solution in a 100 mL Pyrex reactor. Next, 3 wt% Pt as a precursor was added to the photocatalysis solution. By purging the reaction solution with nitrogen gas for 30 minutes, the dissolved O₂ was eliminated. The combined reactants were exposed to light, and the resulting hydrogen gas evolution was detected using gas chromatography (Shimadzu, GC-2014, Molecular Sieve/5 Å column) equipped with a TCD detector. The reactions were achieved between 10:50 a.m. and 1:50 p.m. to ensure the integrity of all experiments carried out in direct sunlight (IST). Solar light density was measured and recorded using a lux meter (TES1332A), and the typical light intensity was measured to be 1358.8 W m⁻² in the summer and 790 W m⁻² in the wintertime.

2.5. Photoelectrochemical analysis

The arranged photocatalysts' photoelectrochemical properties were investigated using a counter electrode (Pt), a reference electrode (Ag/AgCl), and a working electrode covered with the appropriate photocatalyst. In the procedure, 5 milligrams of catalyst were ultrasonically dispersed in a 1:1 water and ethanol mixture with 0.005 mL of Nafion. The mixture was added dropwise to the glassy carbon (GC) electrode, and the electrochemical study was carried out with the help of an electrochemical workstation (Biologic SP150). The electrolyte was maintained as a 0.1 M sodium sulfate solution. A solar simulator (1.5 AM) was used as the light source (SSEM, 300 W, Photo Emission Tech, USA).

2.6. Characterization studies

Using XRD (X-ray diffraction analysis) and Cu K α radiation (=1.5406 Å), the crystalline phase and crystallinity of the sample used to prepare the photocatalyst were ascertained. The PHI Versa Probe III XPS was used to perform the X-ray photoelectron spectroscopy (XPS). Testing was performed using a Shimadzu IRTracer-100 FT-IR spectrometer. Scanning electron microscopy (SEM, TFC, Apreo S) and Transmission electron microscopy were used to examine the sizes and shapes of the nano-composites (TEM, JEOL Japan, and JEM-2100 Plus). The specific surface area and Barrett-Joyner-Halenda (BJH) pore size distribution were calculated using the Autosorb IQ from Brunauer-Emmett-Teller's (BET) Quantachrome Instruments. A UV-vis spectrophotometer was used to record UV-vis diffuse reflectance (UV-DRS) spectra (Shimadzu, UV-3600i Plus). The PL and (TRPL) spectra were analyzed with a fluorescence spectrophotometer (Horiba, Fluorolog-QM).

3. Results and discussion

3.1. Structure analysis

In this study, we prepared N-doped triazole-based g-C₃N₅/TiO₂ S-scheme photocatalysts using 3-AT, citric acid, and TiO₂ as raw materials. Using 3-AT resulted in the formation of a particular



N-rich CN pattern of triazole units, a substitute chemical for synthesizing CN with a larger N-content and low band energy.^{36,37} Fig. 1a depicts the XRD patterns of NCNT_x samples, showing all the significant diffraction peaks of produced TiO₂. TiO₂ (P25) diffraction peaks at 25.3, 36.9, 37.9, 38.5, 48.1, 53.9, 55.3, 62.5, 68.7, 70.5, and 75.2 correspond to plane values (1 0 1), (1 0 3), (0 0 4), (1 1 2), (2 0 0), (1 0 5), (2 1 1), (2 1 3), (1 1 6), (2 2 0), and (1 0 7), respectively. Fig. S1a† shows mainly two peaks at approximately 13° and 27°, corresponding to the graphitic carbon nitride planes (100) and (002). The peak allocated to the (002) plane of NCN has a greater 2θ value than that of the g-C₃N₄ spectrum, which is consistent with an earlier report³⁸ and confirms the formation of the NCN structure. The two triazine and triazole rings in the g-CN unit could be responsible for twisting the sheet structure and reducing the interlayer space in the (002) direction. The XRD patterns of NCNT_x samples contain all of the NCN and TiO₂ peaks in Fig. 1a, which concurs with the findings from HRTEM images. Fig. 1b demonstrates that compared with bare g-CN, the XRD pattern of NCN showed no noticeable change, indicating that NCN retained its molecular structure. The peak frequencies of NCNT_x were slightly shifted from TiO₂ (for example, on the (004) plane of anatase

TiO₂ and the (110) plane of rutile TiO₂) due to the strong intrinsic interactions between TiO₂ and NCN_x. A close connection facilitated the transfer of charge carriers induced by photocatalysis.^{39,40} This can be credited to the effective intrinsic interface between TiO₂ and NCN. The XRD patterns of g-C₃N₄, g-CN (g-C₃N₅), and NCN (N-doped g-C₃N₅) are shown in Fig. S1a.† The slight shift in the location of the NCN peaks from 27° to 27.6° indicated that the N element had been successfully doped into g-CN. This finding suggests that using too much citric acid may cause the production of undesired impurities during the synthesis of N-doped g-C₃N₅.

FTIR analysis was used to examine the fundamental components of NCNT_x samples. Except for a few minor differences, the FTIR spectra of NCNT_x samples revealed similar results in Fig. 1c. The absorption band at 466 cm⁻¹ in the pristine TiO₂ spectrum is caused by the stretching vibrations of Ti–O–Ti and Ti–O in anatase crystals. According to FTIR analysis of the surface functional groups of these samples, the primary spectrum in the range of (1200–1600 cm⁻¹) could be attributed to the C–N/C=N heterocycles of the carbon nitride unit. Another peak was detected at 824 cm⁻¹ for the triazine unit breathing vibration.⁴¹ These peaks were observed to be

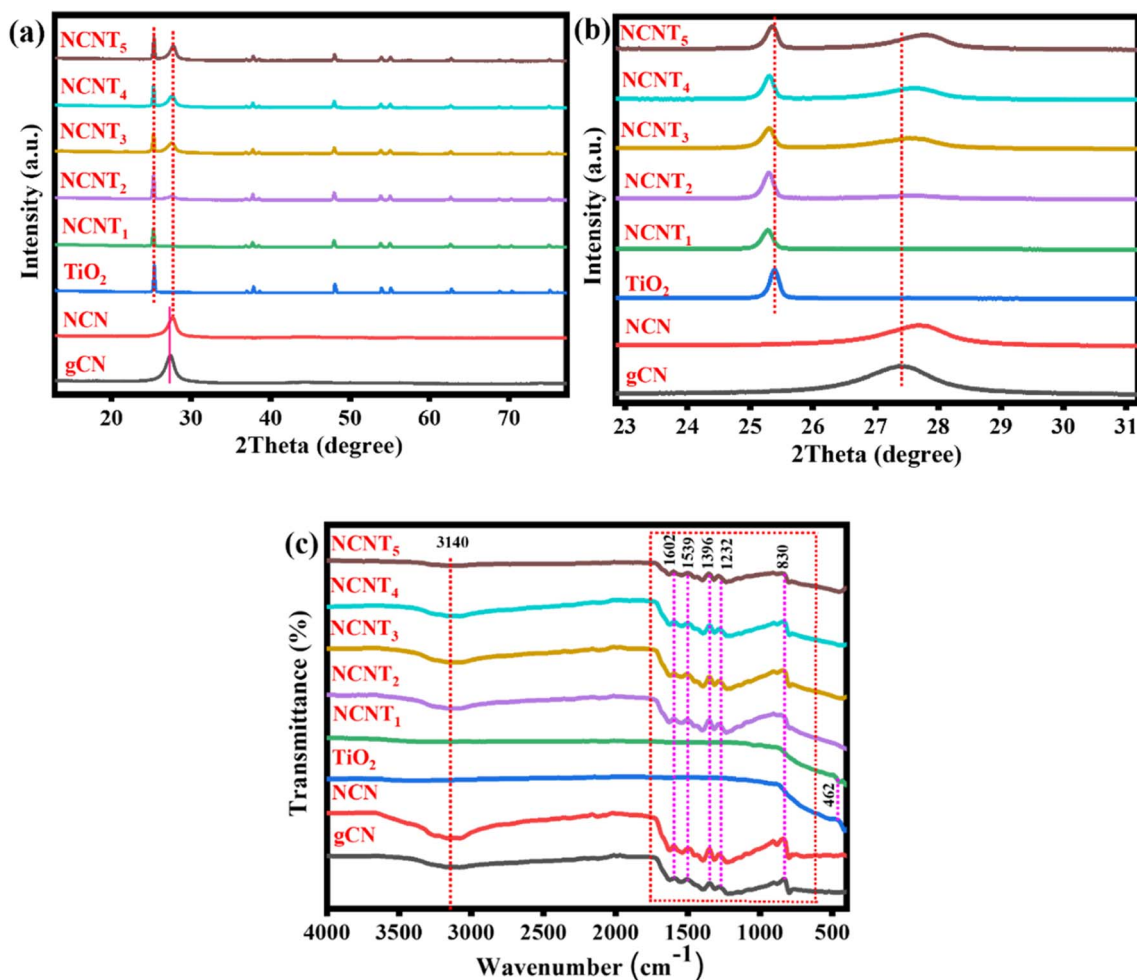


Fig. 1 XRD patterns (a and b) and FT-IR spectra of the (g-CN, NCN, TiO₂, and NCNT_x) (c).



attributed to N–N stretching (1270 cm^{-1}) in triazole-based moieties, and C–N (1334 cm^{-1}) and C=N (1594 cm^{-1}) in triazine units, including both. The peak at 3100 cm^{-1} was caused by the observed stretching vibrations increase of $-\text{NH}_2$ and $-\text{OH}$ of adsorbed H_2O molecules.⁴² Again, the H bond-like connection that gently shifted to a smaller wavenumber and extended peak as compared to NCN at around 1500 cm^{-1} could indicate the formation of protonated graphitic nanosheets.⁴³ Furthermore, the H_2 bond between $-\text{NH}-/\text{NH}_2$ was broken after protonation, as proved by the expansion of the adsorption peaks of $-\text{NH}-$ or $-\text{NH}_2$ groups in the FT-IR spectra at 3500 cm^{-1} to 3000 cm^{-1} .⁴⁴ Despite this, the XRD and FTIR results indicated that these samples were successfully formed and maintained the N-doped $\text{g-C}_3\text{N}_5/\text{TiO}_2$ structure. The FT-IR spectra of $\text{g-C}_3\text{N}_4$, g-CN, and NCN are shown in Fig. S1b.† It was discovered that there was no discernible difference between the FT-IR spectra of $\text{g-C}_3\text{N}_4$ and g-CN, NCN, indicating that NCN retained the molecular structure of g-CN. Nevertheless, XRD and FTIR findings indicated that the $\text{g-C}_3\text{N}_5$ structure was successfully formed and well preserved after N-doping in these samples.

3.2. Morphological characteristics

Fig. 2a–c depict SEM images of the structures and morphologies of bare g-CN, NCN, TiO_2 , and NCNT_x composites. Fig. S2a† clearly shows the rough carbon nitride g-CN sheet layered structure with irregular thickness.⁴⁵ Fig. 2a depicts the sheet-like structure of the nitrogen-doped carbon nitride NCN with a distinct thickness. In Fig. 2b, the TiO_2 sample displays polydisperse spherical morphologies with sizes ranging from 500 to 800 nm. The NCNT_5 composite, produced by heating a combination of 3-AT and TiO_2 , retained the forms of TiO_2 , as depicted in Fig. 2c. Surprisingly, the thermal polymerization SEM of 3-AT (NCN) exhibited a sheet-like appearance on the surface of the TiO_2 , which was closely and uniformly coated. The EDX results of NCN and NCNT_5 in Table S1† show that the weight percentage of nitrogen increased, respectively. Table 2 shows

EDX and XPS analysis results, which confirmed nitrogen enrichment in NCN and NCNT_5 .

The surface morphology and structures of the g-CN, NCN, TiO_2 , and NCNT_x samples were studied using TEM images. As seen in Fig. 2d–f, all the pieces were made up of sheet-like spherical structures. Thermal decomposition and copolymerization can form g-CN ($\text{g-C}_3\text{N}_5$) nanosheets, as shown in Fig. S2c,† which are shorter and lighter than $\text{g-C}_3\text{N}_4$ nanosheets. Fig. S2d† reveals polydisperse spherical morphologies in the 200 nm region in the TiO_2 sample. By the edge of the sheet shape with N-doping content in Fig. 2d, a few nanosheets smaller than 200 nm were generated, resulting in a clear surface area of the g-CN sample. Even though the pieces were sonicated for 45 minutes prior to the TEM measurement, NCN was attached to TiO_2 in a spherical sheet-like manner Fig. 2e. Lattice folds with d -spacings of 0.351 nm and 0.246 nm, respectively, confirmed the (110) and (004) planes of the hexagonal structure seen in NCNT_5 in Fig. 2f. A distinct grain edge indicated that an S-scheme heterojunction layout was formed in the NCNT_x composites. This further validated the structural stability of the NCNT_5 composite. Lattice spacings of 0.351 and 0.246 nm correspond to the (110, 004) planes of the rutile and anatase phases of TiO_2 .^{46,47}

3.3. Sample pore size analysis

N_2 adsorption analysis was also used to limit the textural assets of as-arranged samples. As depicted in Fig. 3a, type (IV) isotherms by H3 hysteresis curves at the comparative pressure series of 0.0 to 1.0 are present in the prepared samples' mesoporous formations. The (BJH) pore size circulation plots (inset) show mesoporous appearances, including the 2–200 nm primary pore size. As determined by BET, the surface areas of NCN, TiO_2 , and NCNT_5 composites were 32.87, 74.68, and $115.35\text{ cm}^3\text{ g}^{-1}$, respectively. The NCNT_5 photocatalyst has a large surface area,⁴⁸ indicating that the recombination rate of photo-generated charge carriers remained low. The increased

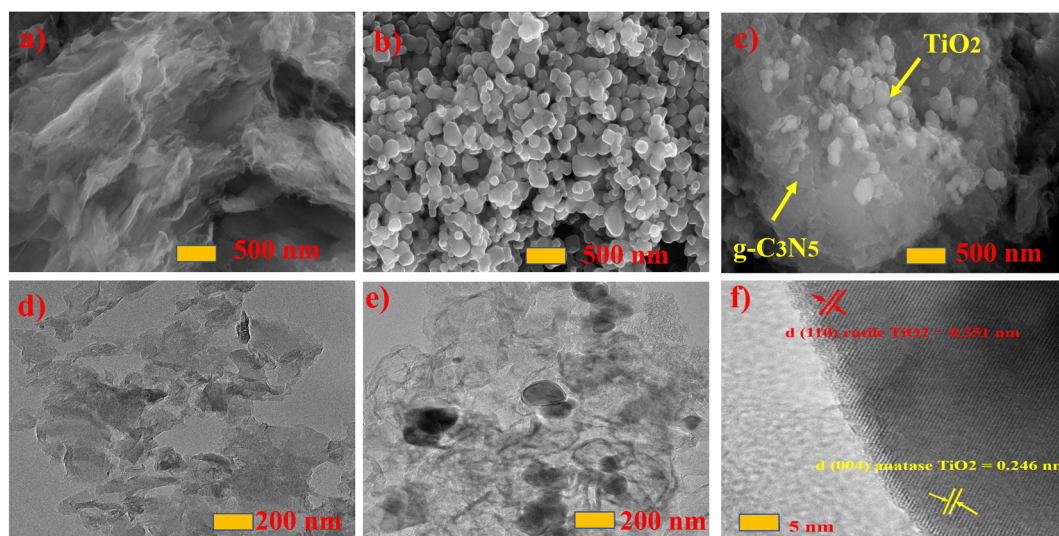


Fig. 2 SEM of the NCN, TiO_2 , and NCNT_5 (a–c), and TEM of the NCN, NCNT_5 , and fast Fourier transform FFT (d–f).



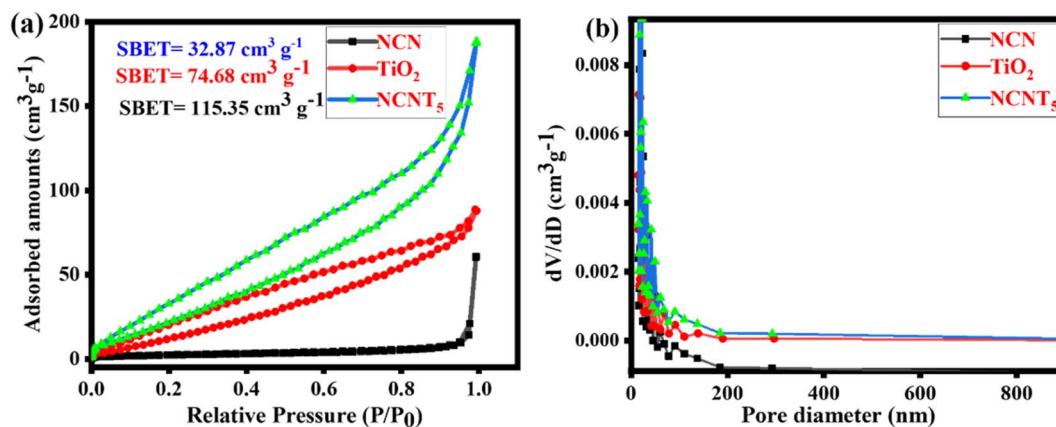


Fig. 3 N_2 adsorption/desorption isotherms (a) and pore size distribution of the NCN, TiO_2 , and $NCNT_5$ samples (b).

diameter range, pore size, migration, and isolation of photo-generated carriers' optical properties all contributed to the increased photocatalytic activity. The $NCNT_5$ composite is advantageous for improved adsorption.^{49,50} According to the findings above, it gives a more significant number of responsive positions for photocatalytic processes, significantly impacting the development of photocatalytic efficiency. TiO_2 and $NCNT_5$ samples have a larger specific surface area than pure NCN. Fig. 3b depicts the distribution of pore sizes. $NCNT_5$ has a broad pore size distribution curve of 8–200 nm, and its pore volume is ($0.289 \text{ cm}^3 \text{ g}^{-1}$), which is two times that of TiO_2 ($0.138 \text{ cm}^3 \text{ g}^{-1}$) and nearly three times that of NCN ($0.105 \text{ cm}^3 \text{ g}^{-1}$). The BET surface area, pore volume, and pore size of all samples are shown in Table 1. TiO_2 and $NCNT_5$ samples have a larger specific surface area than pure NCN. The increased concentration of 3-amino-1,2,4-triazole in the final material may be responsible for the improved specific surface area of $NCNT_5$.

3.4. Surface chemical composition (XPS)

The chemical valence states and surface elemental compositions of $NCNT_5$, NCN, and TiO_2 samples were confirmed using XPS analysis. XPS survey data confirmed that $NCNT_5$, NCN, and TiO_2 composites primarily contain the four elements (Ti, O and C, N) Fig. 4i. The two peaks positioned at (458.05/457.95 eV) and (464.08/463.97 eV) in the high-resolution Ti 2p spectra in Fig. 4a and g, are credited to ($Ti 2p_{3/2}$) and ($Ti 2p_{1/2}$), respectively,⁵¹ indicating the occurrence of Ti^{4+} in TiO_2 and $NCNT_5$. Two chemical positions of O 1s for $NCNT_5$ and TiO_2 were found for the H-R O 1s spectra in Fig. 4b and h, at (529.15/529.37 eV) and (531.37/531.90 eV), which are attributed to O_2^- -type and OH^-

bonds. The peaks from NCN and $NCNT_5$ at (284.65/284.48 eV and (288.24/288.01 eV) in the C 1s H-R spectra in Fig. 4c and e can be a reason for the (C–N and N–C=N) bond groups.⁵² The significant donation peak at (288.24 and 288.01) eV is attributable to the sp^2 -hybridized C bonded to the nitrogen atom within the triazine rings. As shown in Fig. 4d and f, the H-R N 1s spectrum of $NCNT_5$ differs slightly from that of NCN. The N 1s spectrum of NCN and $NCNT_5$ can be separated into five peaks with binding energies of 398.1 eV, 398.9 eV, 399.7 eV, 400.2, 403.7 eV, and 397.5 eV, 398.2 eV, 399.2 eV, 400.1 eV, 402.3 eV, respectively. The dominant peaks at 398.1 and 397.5 eV are attributed to sp^2 -hybridized nitrogen in C-containing triazine rings (C–N=C). In contrast, the peaks at 398.9 and 398.2 eV are usually attributed to tertiary N in N-(C)₃ groups.^{53,54} The amino groups (C–N–H) are indicated by the peaks at 399.7 and 399.2 eV, while π excitation is indicated by the height at 403.7 and 402.3 eV. Another peak at 400.2 and 400.1 eV) corresponding to graphitic N, can be seen in samples NCN and $NCNT_5$, signifying that nitrogen-doped graphitic carbon has been created and is present in the g- C_3N_5 composite.^{55,56} When citric acid was added to g- C_3N_5 , N–N and N=N bond peaks appeared, indicating that nitrogen replaced the carbon atom. Notably, when TiO_2 is coupled with NCN, a slight peak change of Ti 2p, O 1s, C 1s, and N 1s is observed, which applies to the electron screening caused by the variation in electron density. The C–N, N-(C)₃, N–C=N, and C–N=C peaks revealed that the g-CN, NCN, and $NCNT_5$ structures are triazole/triazine unit hybrids (Table 2). The g-CN peaks at 284.70 and 288.64 eV in the C 1s high-resolution spectrum of Fig. 4j correspond to the C–N and N–C=N bond groups. The C–N=C and sp^3 N-(C)₃ bonds were attributed to two peaks at approximately 398.50 and 399.60 eV in the H-R N 1s spectra shown in Fig. 4k.^{3,46} X-ray photoelectron spectroscopy and g-CN and NCN results all supported the idea that the g- C_3N_5 structure was successfully formed and well preserved in these samples before N-doping. In general, surface electron density is negatively related to binding energy.⁵⁷ The internal electric field (IEF) was formed when electrons transferred from NCN to TiO_2 after contact, as shown by the XPS results.

Table 1 Surface characteristics of prepared samples

Samples	S_{BET} ($\text{cm}^2 \text{ g}^{-1}$)	Pore volume ($\text{cm}^3 \text{ g}^{-1}$)	Pore size (nm)
NCN	32.87	0.105	14.30
TiO_2	74.680	0.138	16.23
$NCNT_5$	115.351	0.289	16.21



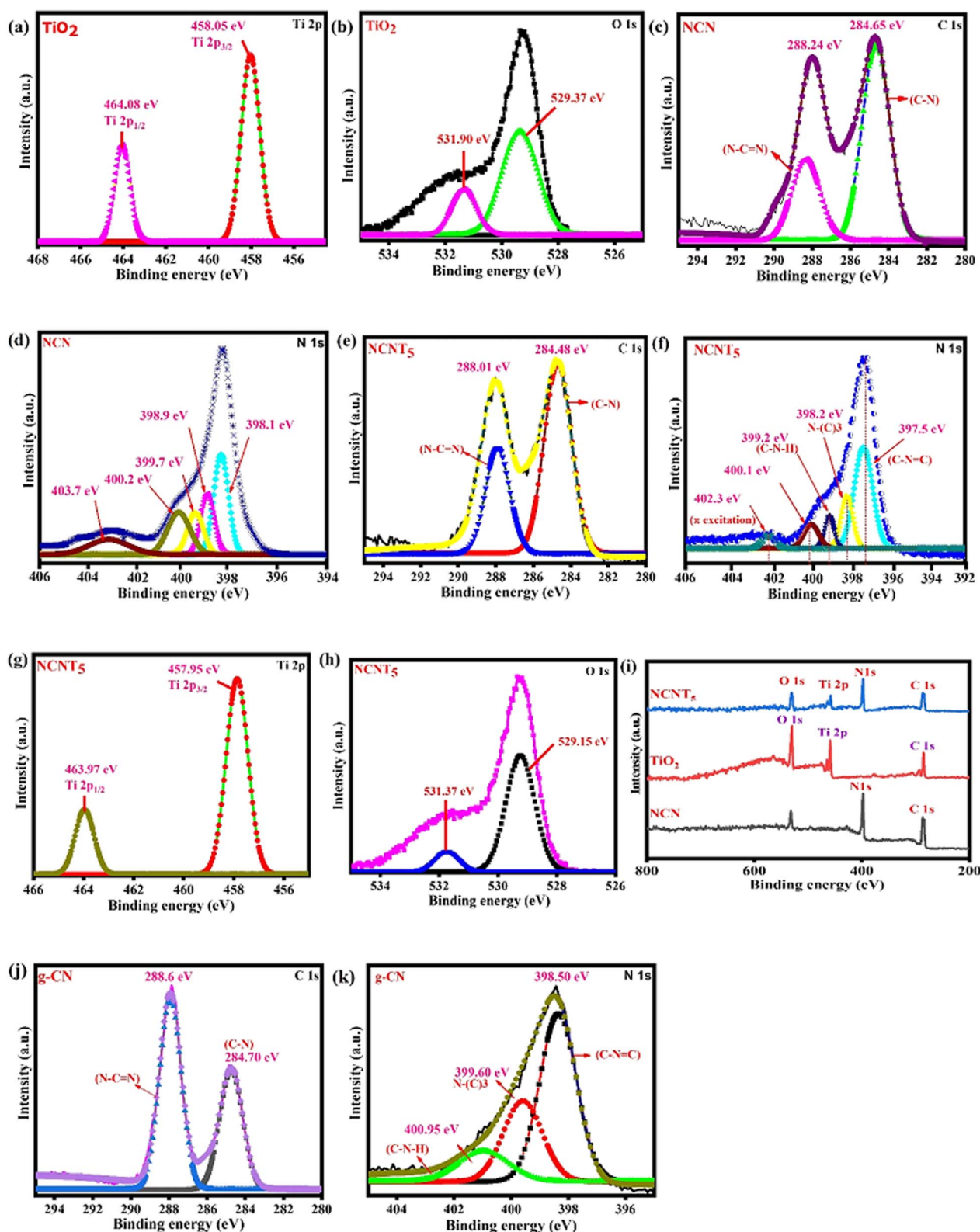


Fig. 4 XPS of (Ti 2p, O 1s) from TiO_2 (a and b), XPS of C 1s and N 1s from NCN (c and d), XPS of C 1s, N 1s, Ti 2p and O 1s from NCNT_5 (e–h), XPS survey spectra of NCN, TiO_2 and NCNT_5 samples (i), and pristine g-CN of C 1s, N 1s (j and k).

3.5. Energy band structure and photoelectric properties

UV-vis spectra were used to characterize the photocatalytic activity of g-CN, NCN, TiO_2 , and NCNT_x , and the correlating

DRS (diffuse reflectance spectra) were generated using the Kubelka–Munk method,⁵⁸ as shown in Fig. 5a and b. In the visible wavelength spectrum, 400–800 nm, the band gaps of the



Table 2 An analysis of deconvoluted XPS spectra revealed the binding energies and valence bond percentages for carbon and nitrogen

Samples	C-N	N-C=N	C-N=C	N-(C) ₃	C-N-H
g-CN	37.61 (284.70)	62.39 (288.6)	53.25 (398.50)	29.11 (399.60)	17.51 (400.95)
NCN	29.82 (284.65)	70.18 (288.24)	44.67 (398.1)	30.84 (398.9)	24.47 (399.7)
NCNT ₅	36.28 (284.48)	63.28 (288.01)	46.90 (397.5)	29.97 (398.2)	23.12 (399.2)

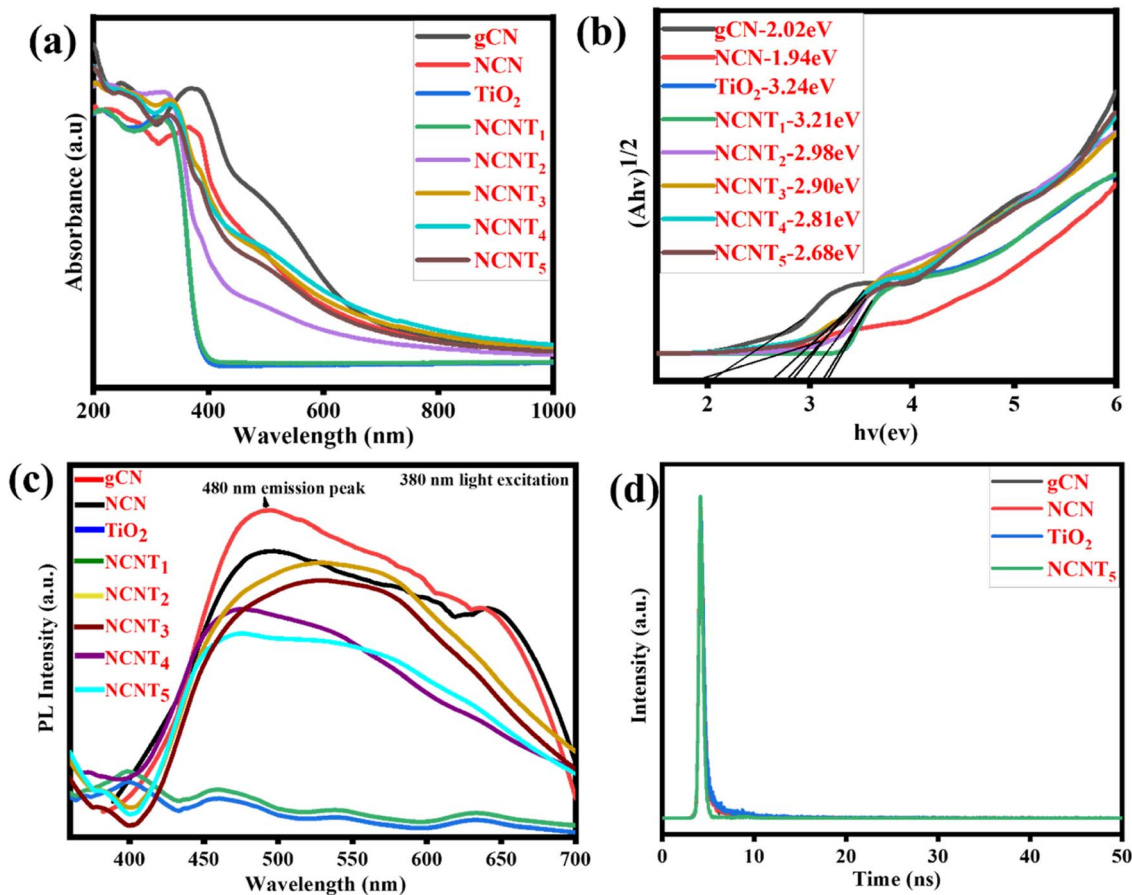


Fig. 5 UV-DRS spectra (a), plots of band gap (b), PL spectra of (g-CN, NCN, TiO₂, and NCNT_x) (c), time-resolved photoluminescence (TRPL) of bare g-CN, NCN, TiO₂, and NCNT₅ (d).

NCN and NCNT_x were red-shifted and the spectral intensity was more significant than that of the g-CN, which may be attributed to the Nitrogen-doped photocatalysts' intrinsic regulation of the interactive band structure or the hierarchical system. The optical properties of the NCNT_x samples were investigated using UV-vis photographs, as illustrated in Fig. 5a and the inset. As previously reported, TiO₂ exclusively shows the optical absorption of UV light.⁵⁹ The standard wide absorption bands of g-CN, NCN, and NCNT_x were observed, relating to the raw band-to-band shift edges of absorbance at 461 to 666 nm, comparable to the optical properties shown in Fig. S3.† As a result, the E_g values of g-CN, NCN, TiO₂, and NCNT_x were estimated to be 2.02, 1.94, 3.24, 3.21, 2.98, 2.90, 2.81, and 2.68 eV Fig. 5b. The higher visible-light spectrum of NCN in comparison to g-C₃N₅ suggested that NCN had more excellent illumination capability over a broader range of visible-light wavelengths. The

correlation among the N 2p orbitals of the connecting azo-nitrogen of triazole-rings, the heptazine π -conjugated process,⁶⁰ which spans the π -conjugation network, is primarily responsible for the more extended absorption of C₃N₅. The increased visible light absorbance of NCNT_x was related to the presence of nitrogen in carbon sites in the NCN unit. It can generate donor regions in the forbidden gap from its N 2p level and contribute too many electrons, thereby refining photocatalytic activity.⁶¹ A UV-Vis spectrum of g-C₃N₄, g-CN, and NCN is shown in Fig. S3.† The energy gap of g-CN is higher than that of g-C₃N₄; after doping nitrogen in g-CN, the band gap was considerably reduced relative to the g-C₃N₄. The results showed that NCN and NCNT_x have a smaller band gap than g-CN, which is helpful for light absorption and raises photocatalytic activity.⁶²



Fig. 5c depicts the photoluminescence spectra of g-CN, NCN, TiO₂, and NCNT_x composite samples under 380 nm light excitation. Similar to prior reports, neither TiO₂ nor NCNT₁ exhibited a detectable emission peak. Although the g-CN and NCN had the highest PL, the peak intensities of the NCNT₂ to NCNT₅ composites were significantly reduced after the NCN was attached to TiO₂. As for the low NCN in the composite,⁶³ the NCNT₅ sample showed no observable emission peaks. The other composites, on the other hand, displayed exceptional photoluminescence signals. Among the NCNT_x ($x = 2, 3, 4,$ and 5) samples, the NCNT₅ sample had low PL intensity, indicating that charge carrier recombination in the composite was critically restricted due to the S-scheme heterojunction structure at the interface of NCN and TiO₂. The overall characteristic peaks of these tests showed that the intensity of their PL emission was reduced following N-doping, with NCNT₅ exhibiting the average PL emission, *i.e.*, the average charge recombination of these samples.^{64,65} An exciting suppression of (e⁻/h⁺) pair recombination may cause the hybrid to generate different photo-induced carriers, activating the photocatalytic reaction.

Time-resolved photoluminescence (TRPL) of bare g-CN, NCN, TiO₂, and NCNT₅ are shown in Fig. 5d, and Table S2† shows the results of a TRPL performed to estimate the lifetime of the charge carriers. The PL emission peak located at approximately 480 nm was determined. Further, bare g-CN, NCN, TiO₂, and NCNT₅ all had average lifetimes of 2.21, 1.98, 2.35, and 1.49 ns. The average charge carrier lifetime of NCNT₅ was 1.49 ns, which is significantly shorter than that of NCN (1.98 ns); this is related to the decreased recombination rate and longer charge carrier lifetime, and was confirmed by Nyquist plots and transient photocurrents.^{66,67} The NCNT₅ heterojunction demonstrated the best charge-transfer efficiency based on the average lifetime of the four samples.

Fig. 6a depicts the cyclic photocurrent curves of pure NCN, TiO₂, and NCNT₅. When a light source is turned on and off, the photocurrent intensities sharply increase and decrease, indicating the formation of photo-induced electrons under visible irradiation. The transient photocurrent density is slightly higher in the NCNT₅ composite than in the NCN and TiO₂ systems, meaning that NCNT₅ can generate more electrons when exposed to visible light. This is stable with the significantly higher current density of the NCNT₅ sample when

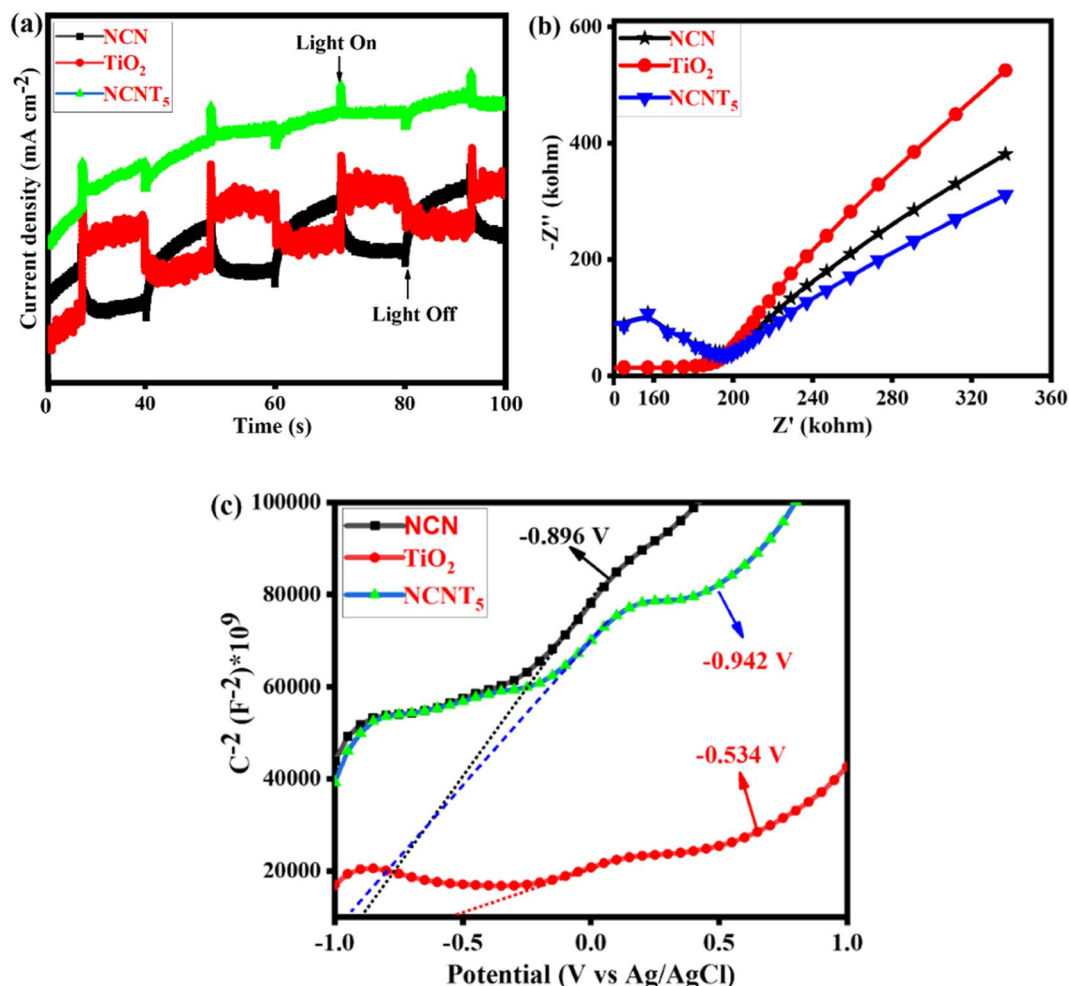


Fig. 6 Photocurrent spectra (a), Nyquist plot (b), and Mott-Schottky plots of NCN, TiO₂, and NCNT₅ samples (c).



Table 3 The band gap, valence band edge, and conduction band edge potentials of NCN, TiO₂, and NCNT₅ catalysts on a standard hydrogen electrode

Semiconductor	E_g (eV)	E_{CB} (eV)	E_{VB} (eV)
NCN	1.94	-0.896	1.04
TiO ₂	3.24	-0.534	2.70
NCNT ₅	2.68	-0.942	1.73

compared to NCN and TiO₂. The results show that NCNT₅ S-scheme heterojunctions are more easily activated by visible light, resulting in extra photo-generated electrons,^{68,69} which indicates improved photocatalytic hydrogen production by powerful visible-light NCNT₅. These findings suggest that NCN's NCNT₅ could improve charge separation and activity, thus enhancing photocurrent responses.

As a result, it is not surprising that the NCNT₅ sample exhibited more excellent photocatalytic activity than bare NCN and TiO₂ due to its greater separation efficiency. Fig. 6b depicts the Nyquist plots of pure NCN, TiO₂, and NCNT₅. The diameter of the semicircle arranged on an EIS plot agrees with the electron-transfer resistance in a sample.⁷⁰⁻⁷² Because NCNT₅ has a smaller arc radius than NCN and TiO₂, the composite has lower energy transference resistance. Forming the S-scheme heterojunction significantly improves the movement and separation efficiency in the NCNT₅ sample. These data show

that NCNT₅ composites outperform single components in electron-hole transportation and partition.

In Fig. 6c, the adequate slopes of the Mott-Schottky plots of the samples revealed their n-type semiconducting nature. As a result, their CB positions can be determined using their plane band capacities, which are determined by the (x) values of their Mott-Schottky curves' linear regions. Thus, the generalized CB positions of NCN, TiO₂, and NCNT₅ samples were -0.89, -0.53, and -0.94 V (vs. Ag/AgCl).⁷³ The band gaps of NCN (1.94 eV), TiO₂ (3.24 eV), and NCNT₅ (2.68 eV) were used to calculate their VB positions, which were 1.04, 2.70, and 1.73 V, respectively, as shown in Table 3.

3.6. Photocatalytic hydrogen production activity

The photocatalytic activity of NCNT_x composites was further validated using an H₂-evolution experiment. According to the controlled experiments, neither the absence of a photocatalyst nor the non-appearance of light irradiation produced measurable H₂. Photocatalytic H₂ production and the consistency of the prepared photocatalysts were tested for triethanolamine 10% as the sacrificial electron donor under sunlight. Fig. 7a displays the hydrogen production amount and maximum H₂ production rate of the g-CN samples. The TiO₂ sample had a lower H₂-evolution rate of (31.2 μmol g⁻¹), which could be the reason for the small surface area and fewer active photocatalytic sites. Close examination of the effects of g-CN precursors and their bonding with the NCNT_x revealed that the order of H₂

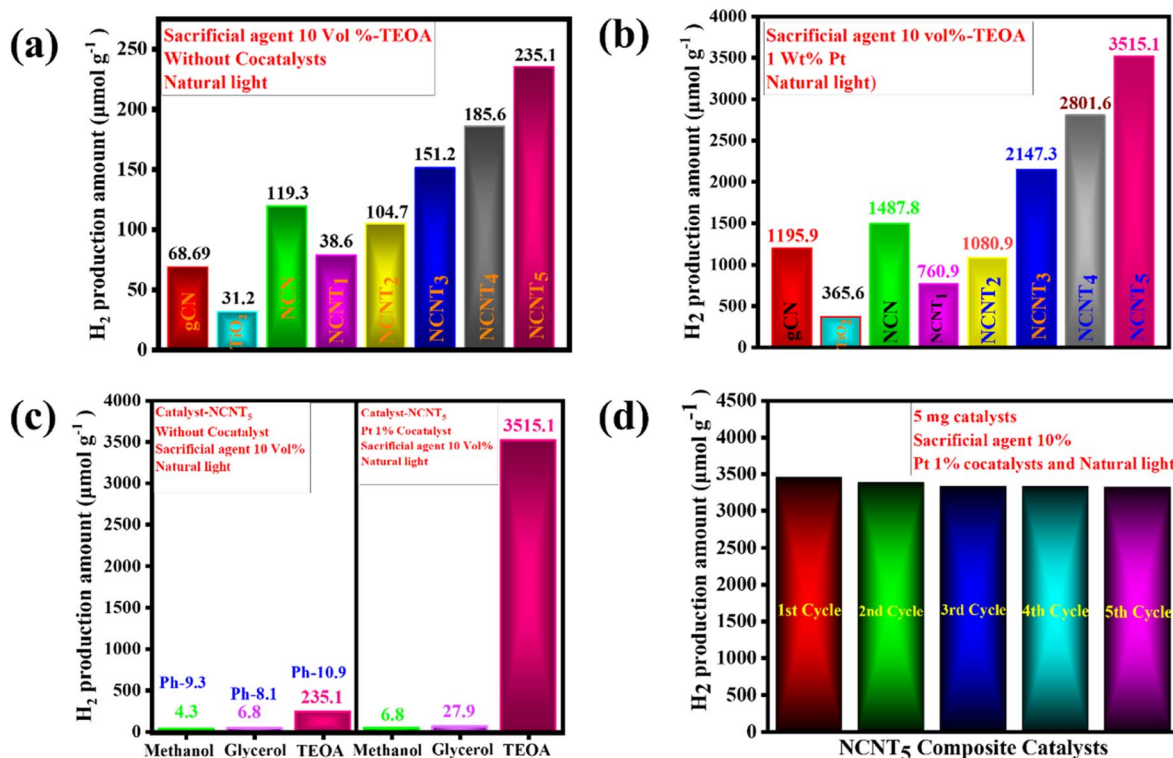


Fig. 7 H₂ generation activity in the photocatalysts. Exposure of sunlight to 5 mg catalyst, TEOA 10 vol% (a), exposure of sunlight to 5 mg catalyst, Pt (1 wt%) cocatalyst, TEOA 10 vol% (b), exposure of sunlight with the 10 vol% sacrificial agents, with and without cocatalyst, and 5 mg catalyst (c), and the re-usability of the NCNT₅ catalyst after exposure, 5 mg catalyst, Pt (1 wt%) cocatalyst, TEOA 10 vol% (d).



evolution under solar light was g-CN ($68.69 \mu\text{mol g}^{-1}$), NCN ($119.3 \mu\text{mol g}^{-1}$), NCNT₁ ($38.6 \mu\text{mol g}^{-1}$), NCNT₂ ($104.7 \mu\text{mol g}^{-1}$), NCNT₃ ($151.2 \mu\text{mol g}^{-1}$), NCNT₄ ($185.6 \mu\text{mol g}^{-1}$), NCNT₅ ($235.1 \mu\text{mol g}^{-1}$) Fig. 4a.

With cocatalysts, the amount of hydrogen production was similarly determined under natural sunlight. The Pt 1 wt% cocatalyst was used with 10% triethanolamine to improve the photocatalyst activity, and the activity of NCNT_x towards H₂ production was investigated. Compared to g-CN, NCN, TiO₂, and NCNT_x without a cocatalyst, the photocatalytic hydrogen evolution rate improved with a cocatalyst. The bare TiO₂ had a poor photocatalytic H₂ production rate of ($365.6 \mu\text{mol g}^{-1}$), possibly because of the rapid recombination of electron-hole pairs. After 3 hours of reaction, the amount of hydrogen produced by these bare g-CN catalysts was close to $1195.9 \mu\text{mol g}^{-1}$. Fig. 7b demonstrates a significant shift in photocatalyst effectiveness to H₂ evolution in the order of NCN ($1487.8 \mu\text{mol g}^{-1}$), NCNT₁ ($760.9 \mu\text{mol g}^{-1}$), NCNT₂ ($1080.9 \mu\text{mol g}^{-1}$), NCNT₃ ($2147.3 \mu\text{mol g}^{-1}$), NCNT₄ ($2801.6 \mu\text{mol g}^{-1}$), and NCNT₅ ($3515.1 \mu\text{mol g}^{-1}$). Related to the new photocatalysts, g-CN, NCN, TiO₂, and NCNT_x, with 1% Pt as a cocatalyst, produced significantly more hydrogen. The increased output could be attributed to the short band gap, more excellent sunlight absorption, and charge carrier division caused by the suitable band orientation of g-CN, NCN, TiO₂, and NCNT_x.

Fig. 7c depicts several sacrificial agents, such as methanol, glycerol, and triethanolamine, resulting from the photocatalytic H₂ production of the NCNT₅ composite. TEOA ($235.1 \mu\text{mol g}^{-1}$), methanol ($4.3 \mu\text{mol g}^{-1}$), and glycerol ($6.8 \mu\text{mol g}^{-1}$) had the highest H₂ production rates for the NCNT₅ composite without cocatalysts. Hydrogen production rates for Pt 1% cocatalysts with NCNT₅ composite were as follows: TEOA ($3515.1 \mu\text{mol g}^{-1}$), glycerol ($27.9 \mu\text{mol g}^{-1}$), methanol ($6.8 \mu\text{mol g}^{-1}$). Furthermore, as shown in Fig. 7c, a system's primary pH significantly impacts photocatalytic activity. The rate of hydrogen evolution was most significant at pH = 10.9 ($235.1 \mu\text{mol g}^{-1}$) and was insignificant in acidic pH. In an acidic environment, triethanolamine is protonated, preventing the loss of H⁺ from TEOA⁺. In a virtual environment, H₂ formation from water is suppressed due to an increase in repulsive force and a decrease in the ability of TEOA to be adsorbed on the photocatalyst surface.⁷⁴

Fig. 7d displays the amount of H₂-evolution for the NCNT₅ composite over five cycles. After each test, a sacrificial agent, triethanolamine, was filled, and the entire hydrogen production

activity was re-evaluated. The quantity of H₂ produced was reserved for up to five cycles, and the cycling experiment demonstrated stability. As a result, the NCNT₅ composite could be a promising material for improving photocatalysis efficiency.

The maximum H₂ production activity completed on a photocatalyst with a cocatalyst created on NCNT₅ is shown in Table 4. The improved photocatalytic activity of NCNT₅ can be attributed to forming an active, S-scheme heterojunction between NCN and TiO₂ and the bond of high electron mobility (Pt) to the TiO₂ surface. Furthermore, as a control experiment, photocatalytic H₂ production activity was carried out using various sacrificial agents such as methanol, glycerol, and TEOA. The rates of H₂ production completed with methanol, glycerol, and triethanolamine were 6.8, 27.9, and 3515.1 $\mu\text{mol g}^{-1}$ for 3 hours, respectively.

3.7. Possible photocatalytic reaction mechanism on the NCNT_x S-scheme heterojunction

Based on the analysis above, it was proposed that a photocatalytic mechanism may enhance catalytic capacity. A traditional type-II heterojunction mechanism was first assumed for the composite (Fig. 8a). TiO₂ and NCN photo-induced electrons (e⁻) migrate from the VB to CB under the influence of visible light, leaving holes in the VB (h⁺). A more negative CB of NCN (-0.89 eV) than TiO₂ (-0.53 eV) caused (e⁻) in the CB of NCN to migrate to TiO₂; the TiO₂ had a more positive VB (2.70 eV) than NCN (1.04 eV), and (h⁺) in the VB of TiO₂ migrated to the VB of NCN.^{83,84} A more practical S-scheme heterojunction was proposed in Fig. 8b in response to the earlier analysis and report based on the XPS and EPR characteristics.⁸⁵ NCN operates as a reduction semiconductor with a greater Fermi level in the NCN/TiO₂ S-scheme heterojunction,⁸⁶ whereas TiO₂ acts as an oxidized semiconductor with lower Fermi levels.⁸⁷ As well as determining Fermi levels (E_f), we obtained band structures of samples using Mott-Schottky plots. A shift from -0.53 to -0.89 V was observed after NCN/TiO₂ treatment, as shown in Fig. 8b. Water reduction potential and E_f levels are represented by the flat band potential.⁸⁸ A heterojunction formed between TiO₂ and NCN initiated spontaneous electron transport to TiO₂ before the equilibrium of the Fermi level. According to the XPS analysis, an internal electric field (IEF) formed at the interface between TiO₂ and NCN. TiO₂ and NCN semiconductors react when visible light irradiates their internal electric fields, in

Table 4 The similarity of the photocatalytic activity in H₂ production from g-C₃N₅ and the TiO₂-based photocatalyst

Composite photocatalysts	Cocatalyst	Sacrificial agent	Light source	H ₂ production ($\mu\text{mol g}^{-1}$)	Year	Ref.
g-C ₃ N ₅	—	Triethanolamine	300 W Xe lamp	28.97	2020	75
g-C ₃ N ₅ /poly(triazine imide)	Pt	Triethanolamine	Natural light	2326.8	2022	76
g-C ₃ N ₄ /TiO ₂	Pt	Triethanolamine	300 W Xe	329	2016	77
S-doped g-C ₃ N ₄	—	Triethanolamine	450 W Xe	986	2017	78
C ₃ N ₅ /CdS	—	Na ₂ S and Na ₂ SO ₃	300 W Xe	7860	2023	79
LaCoO ₃ /C ₃ N ₅	—	Methanol	300 W Xe	956.11	2022	80
P-doped C ₃ N ₅	Pt	Triethanolamine	300 W Xe	318	2020	81
S-doped C ₃ N ₅	Pt	Triethanolamine	450 W Xe	486	2023	82
N doped g-C ₃ N ₅ /TiO ₂	Pt	Triethanolamine	Natural light	3515.1	2022	This work



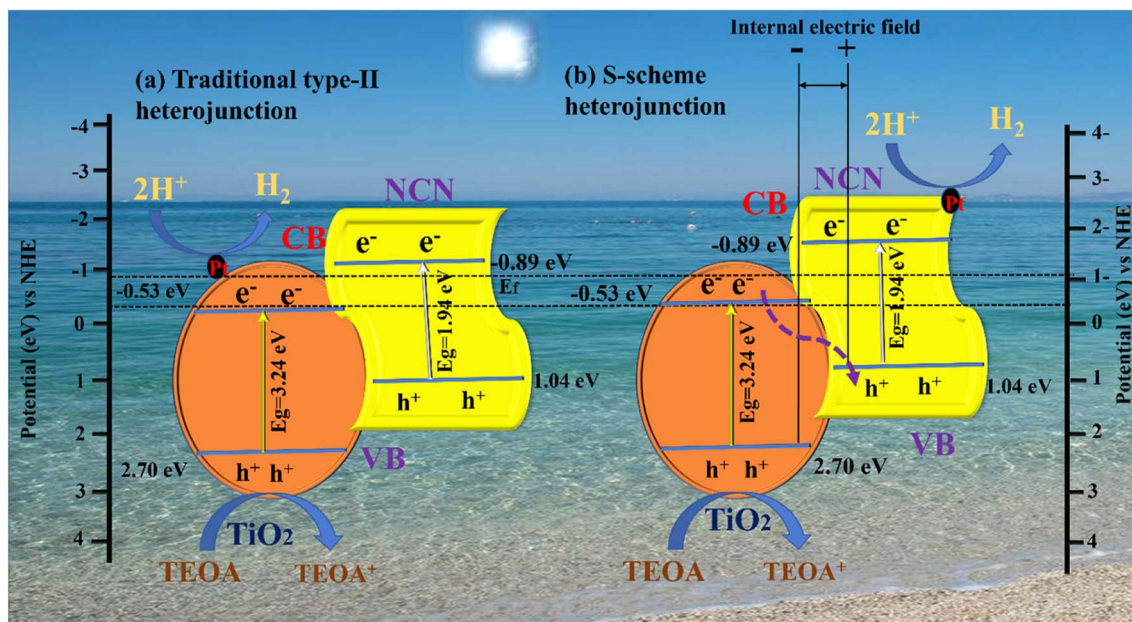
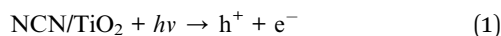


Fig. 8 Proposed charge separation and transfer mechanisms of the NCNT_x photocatalyst: (a) traditional type-II heterojunction, (b) S-scheme heterojunction.

which the electrons in the CB of TiO₂ migrate to the VB of NCN, becoming more effective electrons while retaining more CB holes from NCN and holes VB from TiO₂ (eqn (1)). With the assistance of Pt (eqn (2)), the electrons in the CB of NCN combined with (H⁺) to produce H₂. The oxidation reaction was carried out by the holes that accumulated in TiO₂ (eqn (3)). As a result of electron separation, the CB donates its electrons to an electron acceptor such as H⁺ (eqn (4)). H₂ is formed as a result of this donation. The surface adsorbed (Pt²⁺) was subsequently reduced by electrons deposited in the CB of TiO₂, and the newly designed Pt was deposited on the TiO₂ surface as an efficient cocatalyst for Hydrogen evolution.^{89,90} This composite enhances photocatalytic activity by suppressing the recombination of photogenerated electron-hole pairs, and broadening the light absorption range. In addition, it can increase the efficiency of electron-hole separation. As a result, the photocatalytic activity of the N-doped g-C₃N₅/TiO₂ composite with Pt as cocatalysts is significantly improved.



3.8. DFT calculations

Two possible doping locations were evaluated in the g-CN structure (named C1 and C2). According to earlier research and DFT calculations, the construction energy of a substitutional nitrogen atom in the C1 position was significantly less

than in the C2 site.^{22,36} In this study, however, the construction energy of a substitutional N atom in the C2 position was considerably less than in the C1 area. As a result of its lower construction energy, C2 is more actively supportive of N atom doping. Fig. 9a and b depicts the optimized geometric structure (shown by the yellow ball). Hence, it was concluded that some of the C sites in g-C₃N₅ must have had N species replacing the C atoms to produce N-N=N bonds.⁹¹

Table S3,† the calculated HOMO–LUMO values for g-CN were –5.90 eV (HOMO) and –3.18 eV (LUMO). The inclusion of nitrogen in NCN as compared to g-CN leads to a linear destabilization of the HOMO value (–5.73 eV) and stabilization of the LUMO value (–3.34 eV), resulting in a reduced band gap of 2.34 eV as compared to the g-CN molecule (2.72 eV) Fig. 9c. These analyses revealed that the calculated results demonstrated consistent trends with the experimental values. Furthermore, we employed a combination of hybrid B3LYP, PBE₀, and meta-hybrid M06 and M06-2X functionals to simulate the absorption studies with the 6-31+G* basis set.^{92–94} The table revealed a clear linear correlation between the absorption values and the Hartree–Fock values within the functional. The absorption range for both molecules, determined using the M06-2X functional, closely matched the experimentally measured absorption values, falling within the range of 390 nm to 394 nm, while the experimental values ranged from 365 nm to 375 nm (Fig. 9d). A broad absorption band was observed for g-C₃N₅ and nitrogen-doped g-C₃N₅, with absorption edges at 461 and 484 nm (Table S4†), consistent with DFT calculations. The natural transition orbital (NTO) maps further validated the presence of a similar absorption range in both the g-CN and NCN molecules.⁹⁵ The NTOs for both the holes and electrons



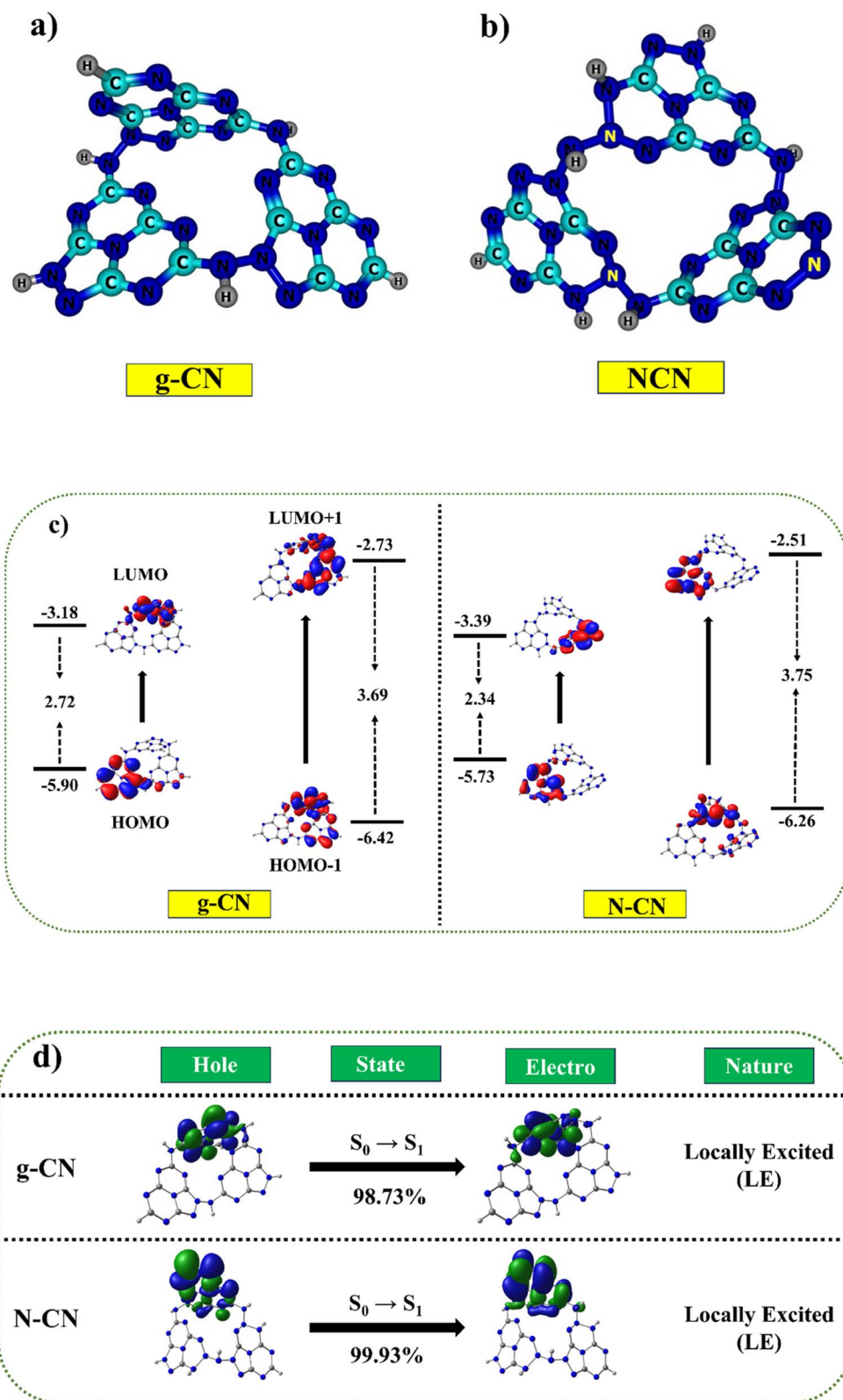


Fig. 9 The probable existing forms of $g\text{-C}_3\text{N}_5$ and N-doped $g\text{-C}_3\text{N}_5$ (a and b). Correlation diagram for the frontier orbitals (FMOs in eV) of g-CN and NCN trimers (iso-surface value = 0.02 au.) (c). Hole-particle NTOs (iso-surface value = 0.02 au.) of g-CN and NCN molecules with excited state transition character (d).



were predominantly localized within the sole monomer units, indicating locally excited characteristics. The calculated energies exhibited a remarkable agreement with the experimentally measured values, highlighting the noteworthy correspondence achieved for the ground and excited state energies using the O3LYP and M06-2X functionals, respectively.

4. Conclusion

We have reported a new photocatalyst using the N-doped g-C₃N₅/TiO₂ composite as an effective photocatalyst for visible-light-assisted photocatalytic hydrogen production. The XRD and XPS results have demonstrated fruitful nitrogen doping on the C₂ site of g-C₃N₅. The DFT calculations, PL, and XPS results show that the nitrogen doping occurred on the C₂ site of g-C₃N₅; as indicated by the fluctuation in charge density, constant PEC, and PL spectra, NCNT_x exhibits excellent photo-generated carrier separation and charge transfer, enhancing photocatalytic activity. Photocurrent and EIS analysis predicted the S-scheme heterojunction mechanism to explain the electron process flow in composites, especially in the presence of light. The efficacy of H₂ production on the nitrogen-doped g-C₃N₅/TiO₂ for 3 hours (3515.1 μmol g⁻¹) without a co-catalyst is about three times that of N-doped g-C₃N₅. The efficacy of the nitrogen-doped g-C₃N₅/TiO₂ catalyst with Pt as the cocatalyst significantly showed a ten-fold increase in performance as compared to the N-doped g-C₃N₅/TiO₂ without cocatalyst. This work highlights the photocatalytic reaction of the N-doped g-C₃N₅/TiO₂ composite with Pt as a cocatalyst. It demonstrates a promising strategy for the efficient production of hydrogen through the S-scheme mechanism.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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