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Rationally designed In–CeO₂/g–C₃N₄ S-scheme heterojunction photocatalyst with tuned redox ability for the photocatalytic degradation of pharmaceutical contaminants

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Herein, the synthesis of an indium-doped cerium oxide/graphitic carbon nitride (In–CeO₂/g–C₃N₄) S-scheme heterojunction aimed at optimizing photocatalytic degradation under visible light for the remediation of pharmaceutical wastewater is reported. The materials were synthesized via a hydrothermal process, in which pure CeO₂ and In-modified CeO₂ (In–CeO₂) were initially synthesized, followed by the incorporation of g–C₃N₄ to produce the heterojunction. A series of characterization methods, such as X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), and scanning electron microscopy (SEM), validated the effective synthesis and structural integrity of CeO₂, In–CeO₂, and In–CeO₂/g–C₃N₄. The optical bandgap of the samples was determined, presenting a reduction from 2.97 eV for CeO₂ to 2.69 eV for In–CeO₂/g–C₃N₄, which facilitated better visible-light absorption. Photocurrent and electrochemical impedance spectroscopy (EIS) characterizations indicated enhanced charge separation and reduced recombination in the In–CeO₂/g–C₃N₄ heterojunction. Photocatalytic experiments for the degradation of levofloxacin (LVX) demonstrated that the In–CeO₂/g–C₃N₄ heterojunction achieved 85% degradation, significantly higher than those achieved by In–CeO₂ (63%) and CeO₂ (44%), highlighting the enhanced photocatalytic performance of the heterojunction. The higher photocatalytic activity is attributed to the formation of an S-scheme charge migration channel, enabling efficient charge separation. Results indicate that the In–CeO₂/g–C₃N₄ heterojunction has great potential for water purification applications, particularly in degrading drug contaminants.

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1. Introduction

Utilizing visible light for the photocatalytic degradation of organic pollutants is an economical and sustainable cleantech solution to the escalating environmental pollution and water contamination.^{1,2} Despite its promise, the development of photocatalysts is a challenging process because the

conventional semiconductor materials, including TiO₂,^{3,4} ZnO,^{5,6} and CeO₂,^{7,8} have low quantum efficiency due to their electronic band structures (wide optical bandgaps), which prevent harnessing the visible part (~43%) of solar light, and their photogenerated charge carriers (electron-hole pairs) recombine rapidly limiting their availability.^{9–11}

Cerium oxide (CeO₂), commonly known as ceria, is an emerging material in the realm of photocatalysts, which is resistant to photocorrosion and is chemically and thermally stable.^{12,13} The applicability of ceria as a promising photocatalyst is explicitly limited by its weak visible-light activity and high electron-hole pair recombination, which are crucial factors for visible-light-driven photocatalysis.^{14–16} Several investigations, including metal-doping, indicate that cerium oxide modification tunes the electronic structure and enhances the quantum efficiency.^{16–19} The rapid electron-hole recombination can be suppressed by coupling ceria with another photocatalytic material through the formation of heterostructure junctions, thereby increasing the availability of charge carriers for photocatalytic reactions.^{20–23}

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Assembling two different photocatalytic materials with distinct electronic properties to construct heterostructure junctions enhances charge separation, which is crucial for significant photocatalytic performance.^{24–26} These materials possess distinct electronic band structures that facilitate the migration and separation of photogenerated electron–hole pairs, enhancing the photocatalytic performance.^{27,28} For instance, S-scheme heterojunction formation involves the interfacial contact of two photocatalysts, in which band structure alignment results in the accumulation of holes in the valence band of one of the combining photocatalysts and electrons in the conduction band of the other photocatalyst, which is mainly compelled by the internal electric field.²⁹ Graphitic carbon nitride g-C₃N₄ (g-CN), a polymeric compound with a layered structure of tri-s-triazine units, exhibits high thermal and chemical stability with excellent visible-light activity. The distinguished properties, which include non-toxicity, a unique metal-free framework, and a semiconductor with a medium band gap, enable its use as a sustainable catalyst for photo-degradation applications. Despite these characteristics, g-CN exhibits low quantum efficiency due to a low absorptivity coefficient and sluggish electron–hole separation, which can be improved by modifying g-CN. Various reports present g-CN as a promising material for the fabrication of heterostructure junctions, as its unique structural framework favours interfacial contact.^{30,31} For instance, ZrO₂/g-CN,³² Ce(MoO₄)₂/g-CN, g-CN/Bi₂O₂CO₃-Bi₄O₇,³³ Nd/Ni-LaFeO₃/g-CN,³⁴ CdMoO₄/g-CN,³⁵ ZnO/g-CN,³⁶ Ni-MOF/g-CN,³⁷ and ZnAl-LDH/g-CN³⁸ include the g-CN-based material designs for wastewater decontamination applications. The findings reveal that these composite designs not only increase the optical response but also facilitate charge separation and transport primarily through the formation of heterojunctions.

Based on the facts described above, we synthesized a visible-light-activated In-CeO₂/g-CN S-scheme heterojunction to facilitate charge separation and transport, thereby augmenting the effective photocatalytic removal of pharmaceutical pollutants. The hydrothermal method was used to synthesize pure CeO₂ and its indium-modified form, In-CeO₂, while melamine was calcinated for its thermal polymerization to prepare g-CN. Both the components, In-CeO₂ and g-CN, were subjected to ultrasonication to fabricate the In-CeO₂/g-CN heterojunction. The synthesized materials were characterized to investigate their crystal structure formation, thermal stability, microstructure, optical activity, and electrochemical response. The photocatalytic efficiency of In-CeO₂/g-CN was estimated by degrading levofloxacin, a typical pollutant, showcasing the effect of heterojunction formation on photocatalytic performance. The present work aims to significantly contribute to the design of heterojunction materials for the photocatalytic degradation of pharmaceutical contaminants in wastewater remediation.

2. Experimental

2.1 Chemicals

The chemicals, including ceric ammonium nitrate (Sigma-Aldrich, (NH₄)₂[Ce(NO₃)₆], ≥ 98.5%), indium nitrate (Sigma-

Aldrich, In(NO₃)₃, 99.99%), and melamine (Sigma-Aldrich, Powder, 99%), were used in the synthesis of CeO₂, In-CeO₂, and In-CeO₂/g-CN materials. Levofloxacin (LVX, C₁₈H₂₀FN₃O₄), ethylenediaminetetraacetic disodium salt (Sigma-Aldrich, EDTA-2Na, 99%), silver nitrate (AgNO₃), isopropyl alcohol (Sigma-Aldrich, IPA, 99%), and benzoquinone (Sigma-Aldrich, BZQ, 99%) were used in the photocatalytic activity investigation. All the standards were prepared in DI water ($k < 6 \mu\text{S cm}^{-1}$).

2.2 CeO₂ and In-CeO₂ synthesis

The facile hydrothermal method was applied to synthesize pure CeO₂ and In-CeO₂ materials. Initially, 3 g of (NH₄)₂[Ce(NO₃)₆] was added to 70 mL of DI water while stirring until the formation of a clear solution, followed by the addition of 0.15 g In(NO₃)₃. The pH was raised to ~10 with drop-by-drop addition of NH₄OH, and the solution was poured into a Teflon cup enclosed in an autoclave (stainless steel-made), following the heating of the solution at 180 °C for 12 h. The precipitates collected were thoroughly washed with DI water multiple times to neutralize the pH and remove unreacted precursors, and then dried at 55 °C for 2 h.

2.3 Preparation of g-CN powder

The g-CN powder was prepared from melamine through thermal condensation.³⁹ Experimentally, 2 g of the precursor powder was placed in a 25 cc (porcelain) crucible and heated at 550 °C for 6 h at 5 °C min⁻¹. Upon the completion of the heating process, the crucible was removed from the furnace and allowed to cool naturally in the air. The pale, yellowish-colored g-CN formed was collected and stored in a dry environment.

2.4 In-CeO₂/g-CN construction

The g-CN-based heterojunction of modified In-CeO₂ was formed using an ultrasonication method. In the experiment, 0.9 g of In-CeO₂ was poured into DI water (100 mL) and sonicated with an ultrasonic probe for 1 hour. Similarly, in a beaker (100 mL, DI water), 0.1 g of g-CN powder was separately sonicated. The resulting suspensions were mixed, followed by sonication again for 1 hour to enhance the interaction and dispersion of In-CeO₂ with g-CN, assembling the In-CeO₂/g-CN heterojunction (Fig. 1).

2.5 Characterization

The crystal structure formation and phase purity of the fabricated materials were investigated by powder XRD (X-ray Diffractometer, Shimadzu 6100 AS, Cu-K α radiation, $\lambda = 0.154$ nm) and FTIR spectroscopy (Shimadzu IRAffinity-1S Spectrophotometer), while for thermal stability, TGA (Thermo Plus Evo, TG8120 Rigaku) was performed. The morphology was explored by SEM (Scanning electron microscope, FEI S50) and optical activity by UV-vis spectroscopy (Double-Beam Spectrophotometer, Jenway/6850). The electrochemical response was recorded on a three-electrode potentiostat (reference electrode = Ag/AgCl, working electrode = indium tin oxide-coated glass, and



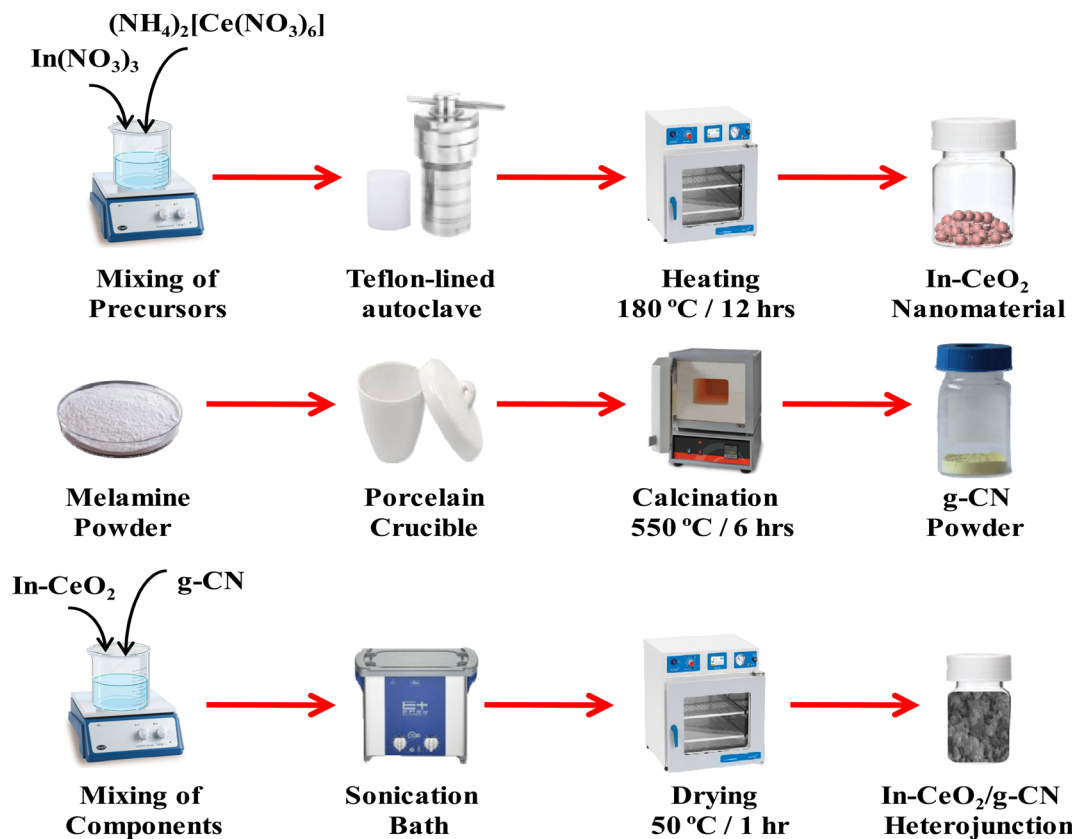


Fig. 1 Schematic of the synthesis of CeO₂ and In-CeO₂ (hydrothermal), g-CN (calcination), and In-CeO₂/g-CN (ultrasonication).

auxiliary electrode = Pt wire) in 1 M Na₂SO₄ electrolytic solution.

2.6 Photocatalytic (PC) efficiency

The PC efficiency of CeO₂, In-CeO₂, and In-CeO₂/g-CN photocatalysts was evaluated by degrading LVX under a Xe lamp (300 W, UV cutoff filter $\lambda > 420$ nm) placed 20 cm above the reaction mixture. Initially, 0.05 g of CeO₂, In-CeO₂, and In-CeO₂/g-CN were dispersed in LVX (10 mg L⁻¹, 100 mL) solutions in three separate beakers. The resultant mixtures (LVX + photocatalyst) were kept in the dark and stirred for 40 minutes to acquire LVX adsorption-desorption equilibria on the catalyst surface. Afterward, the solutions were exposed to light to initiate LVX degradation, following the separation of samples from the working mixture to investigate the degradation process. The catalyst In-CeO₂/g-CN was recovered by centrifugation and reused for LVX degradation under the same conditions. The percentage degradation (D) was calculated using the relation $D(\%) = (1 - C_t/C_0) \times 100$,⁴⁰ where C_t represents the LVX concentration at the specified time interval, while C_0 is its initial concentration.

3. Results and discussion

3.1 Structural features

The crystal structure formation and phase purity of the synthesized materials were verified *via* XRD patterns ($2\theta =$

10° – 80°), which are shown in Fig. 2(a). The peaks present at $2\theta = 28.56^\circ$, 33.16° , 47.45° , 56.34° , 59.14° , 69.53° , 76.92° , and 79.12° , corresponding to the (111), (200), (220), (311), (222), (400), (331), and (420) diffraction planes, are consistent with the standard data (00-034-0394), confirming the formation of CeO₂.⁴¹ The indium-modified material shows a variation in its diffraction peaks, which correspond to the structural changes caused by the different ionic sizes of dopant indium and the cerium host.⁴² Notably, the absence of any additional diffraction peaks for pure CeO₂ and its indium-modified composition In-CeO₂ confirms the phase purity and insertion of indium ions in the CeO₂ lattice. The lower-intensity diffraction peaks in the XRD pattern of In-CeO₂/g-CN correspond to the interaction between In-CeO₂ and g-CN, causing microstructural changes.^{43,44} The distinct lattice vibrations of the synthesized materials were confirmed from the FTIR spectra, as displayed in Fig. 2(c). The presence of distinctive Ce–O and Ce–O–Ce vibrations at 460 cm^{-1} and 1052 cm^{-1} confirms the formation of the synthesized materials.⁴⁵ The peaks at 1640 cm^{-1} , 1426 cm^{-1} , 1324 cm^{-1} , and 1252 cm^{-1} in the spectra of g-CN and In-CeO₂/g-CN can be attributed to C–N heterocyclic and aromatic stretching vibrations, while the peak at 810 cm^{-1} corresponds to the bending vibration (s-triazine units) of the g-CN framework.^{46–48} The additional –OH stretching and –OH bending observed indicate moisture adsorption on the material's surface.^{49,50} The thermal TGA plots showcasing the mass loss of the material against the



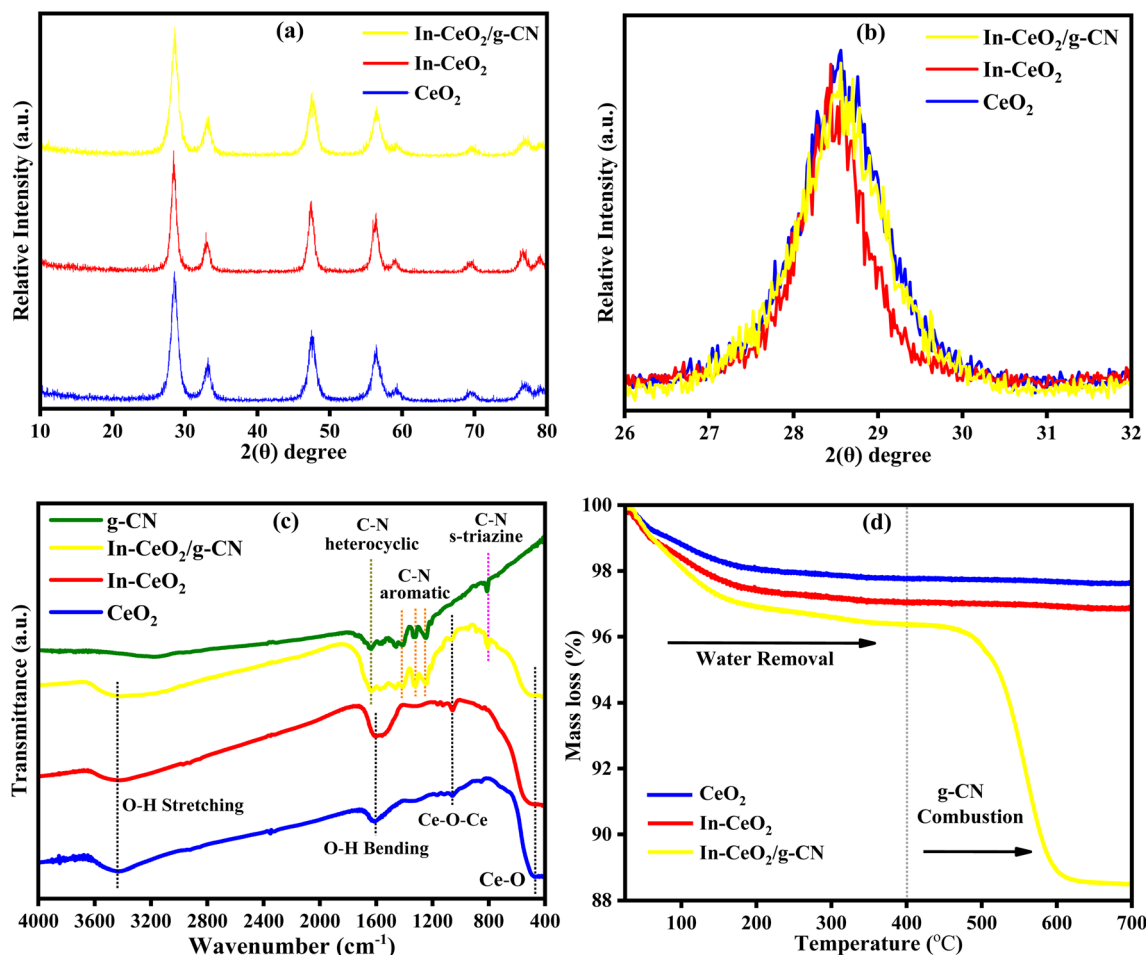


Fig. 2 (a) XRD patterns, (b) enlarged view of the diffraction patterns ($2\theta = 26\text{--}32^\circ$), (c) FTIR spectra, and (d) TGA plots of the synthesized pure CeO₂, modified In-CeO₂, and the In-CeO₂/g-CN heterojunction.

applied temperature of CeO₂, In-CeO₂, and In-CeO₂/g-CN are shown in Fig. 2(d). In the lower temperature zone (<300 °C), minute weight losses of 2.29% (CeO₂), 3.03% (In-CeO₂), and 3.60% (In-CeO₂/g-CN) were observed, which are due to moisture removal. For the g-CN-based heterojunction material, in the higher temperature zone (400–600 °C), 7.93% of weight loss was witnessed, which corresponds to g-CN combustion.⁵¹

3.2 Morphological analysis

The microstructure and morphology of the synthesized CeO₂, In-CeO₂, and In-CeO₂/g-CN materials were examined by SEM analysis, and the micrographs are presented in Fig. 3. For CeO₂, a fine granular-type aggregation was observed, while for In-CeO₂, the symmetry changes to irregular-sized crystallites with varying sizes. Indium modification not only changes the microstructure from granules to crystallites, but also from aggregation to dispersion of the material. The g-CN integration further increases dispersion, preventing agglomeration, as evident in Fig. 3(d), which is substantial for photocatalytic applications.

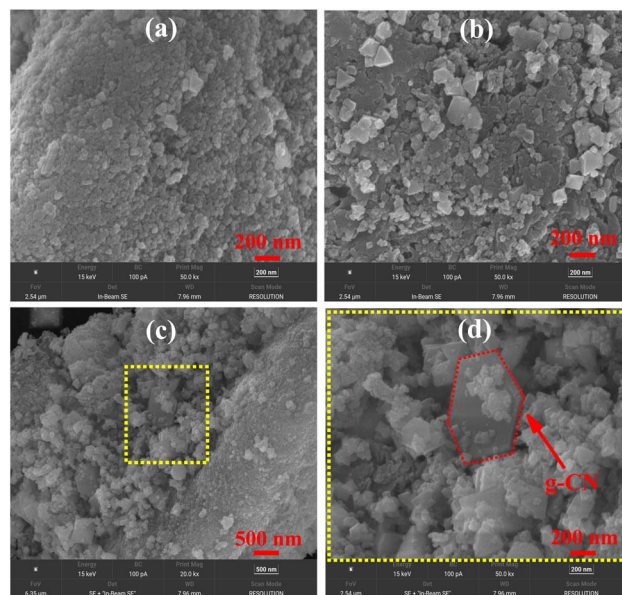


Fig. 3 SEM images of (a) CeO₂, (b) In-CeO₂, and (c and d) In-CeO₂/g-CN.



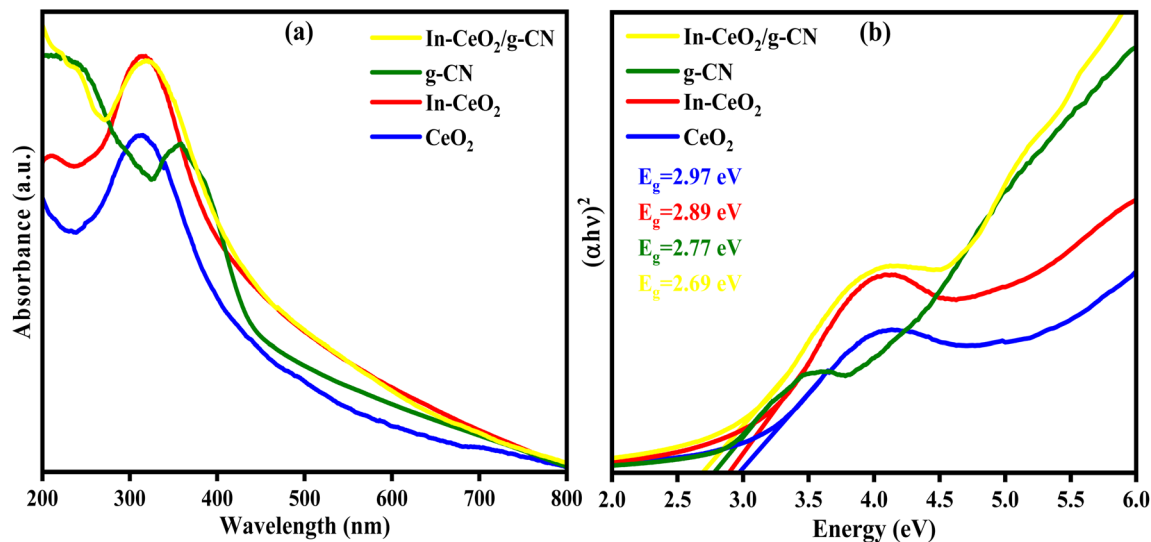


Fig. 4 (a) UV-visible absorption spectra and (b) bandgap calculation from the Tauc plot model of the synthesized CeO₂, In-CeO₂, g-CN, and In-CeO₂/g-CN.

3.3 Optical properties

The optical properties of CeO₂, In-CeO₂, g-CN, and In-CeO₂/g-CN materials were investigated by UV-vis absorption spectroscopy, and the absorption spectra observed for different materials are presented in Fig. 4(a). The synthesized materials feature absorption edges extending into the visible region. Notably, indium-modification and heterojunction formation with g-CN considerably enhances visible-light absorption, as evident from the red-shift in the absorption edge.^{52,53} Fig. 4(b) presents the Tauc plots generated to calculate the optical bandgap (E_g),⁵⁴ and the materials CeO₂, In-CeO₂, g-CN, and In-CeO₂/g-CN feature an E_g of 2.97 eV, 2.89 eV, 2.77 eV, and 2.69 eV, respectively. The In-CeO₂/g-CN heterojunction ($E_g = 2.69$ eV) exhibits increased absorption, facilitating the separation of electron-hole pairs under visible light and rendering it promising for photocatalytic applications.

3.4 Electrochemical response

The electrochemical responses of CeO₂, In-CeO₂, g-CN, and In-CeO₂/g-CN materials were investigated to elucidate charge transfer kinetics and electron-hole recombination rates. The EIS results, presented as Nyquist plots in Fig. 5(a), reveal a distinct electrochemical response. The semicircle diameter in the Nyquist plot reflects the charge transfer resistance (R_{ct}) at the working electrode-electrolyte interface.⁵⁵ Notably, the In-CeO₂/g-CN heterojunction exhibits a smaller semicircle diameter compared to its components, g-CN and In-CeO₂, indicating lower R_{ct} and faster charge transfer kinetics.⁵⁶⁻⁵⁸ The light-on photocurrent generation for the materials CeO₂, In-CeO₂, g-CN, and In-CeO₂/g-CN is presented in Fig. 5(b). The significantly increased photocurrent density observed for In-CeO₂/g-CN can be attributed to enhanced charge separation due to band structure alignment, which suppresses rapid electron-

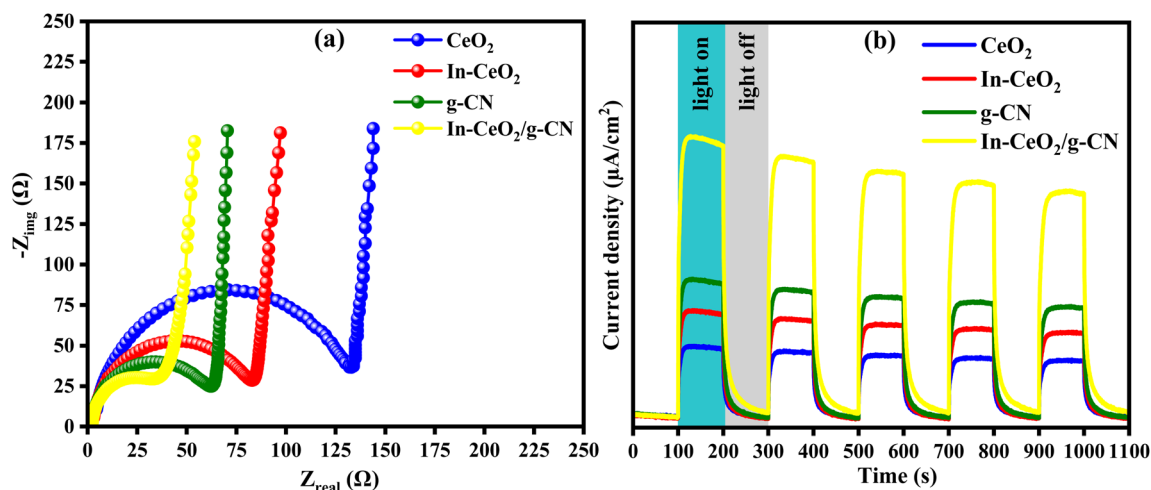


Fig. 5 (a) Nyquist plots and (b) photocurrent responses of the CeO₂, In-CeO₂, g-CN, and In-CeO₂/g-CN materials.

hole recombination.^{59,60} The heterojunction formation enhances charge transport, thereby increasing the availability of electron-hole pairs or their participation in the photocatalytic process.

3.5 PC activity

The PC activity of CeO_2 , In-CeO_2 , and $\text{In-CeO}_2/\text{g-CN}$ materials was estimated by degrading LVX. The UV-vis absorption data of the LVX samples separated from the aliquot at specified time intervals (in the presence of $\text{In-CeO}_2/\text{g-CN}$) are presented in Fig. 6(a). The absorption intensity at λ_{max} corresponds to the LVX concentration, which decreases, indicating LVX degradation. The absorption intensity rapidly declines in the presence of the photocatalyst $\text{In-CeO}_2/\text{g-CN}$ as compared to In-CeO_2 and CeO_2 , which degrade LVX to a lower extent. In Fig. 6(b), the LVX degradation (%) over the synthesized catalysts is presented, which follows the order, CeO_2 (44%) < In-CeO_2 (63%) < In-

$\text{CeO}_2/\text{g-CN}$ (85%). The order of photocatalytic efficiency is consistent with the optical properties and electrochemical responses of the photocatalysts, which feature facilitated electron-hole separation and transport in $\text{In-CeO}_2/\text{g-CN}$, revealing its promising potential for photocatalytic applications.

The kinetics study of LVX degradation over the photocatalysts, CeO_2 , In-CeO_2 , and $\text{In-CeO}_2/\text{g-CN}$, is shown in Fig. 7(a), which presents 1st-order kinetics for LVX degradation. The rate constants were calculated as 0.0075 min^{-1} , 0.0123 min^{-1} , and 0.0198 min^{-1} , corresponding to CeO_2 , In-CeO_2 , and $\text{In-CeO}_2/\text{g-CN}$. The scavenging study presented in Fig. 7(b) for LVX degradation in the presence of a photocatalyst with the highest photocatalytic efficacy, $\text{In-CeO}_2/\text{g-CN}$, was performed using EDTA, AgNO_3 , IPA, and BQ for trapping holes (h^+), electrons (e^-), hydroxyl radicals (HO^\bullet), and superoxide radicals ($\text{O}_2^{\bullet-}$), respectively. In the presence of AgNO_3 , the decline in LVX degradation was not significant, but in the

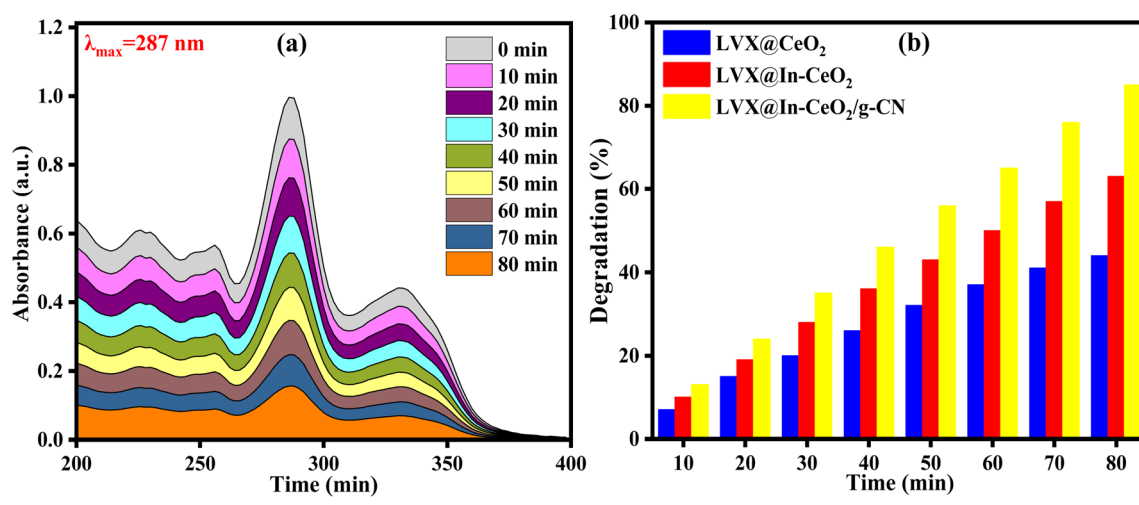


Fig. 6 (a) UV-vis absorption spectra of the samples collected during LVX degradation in the presence of $\text{In-CeO}_2/\text{g-CN}$ and (b) comparison of the catalytic efficiency.

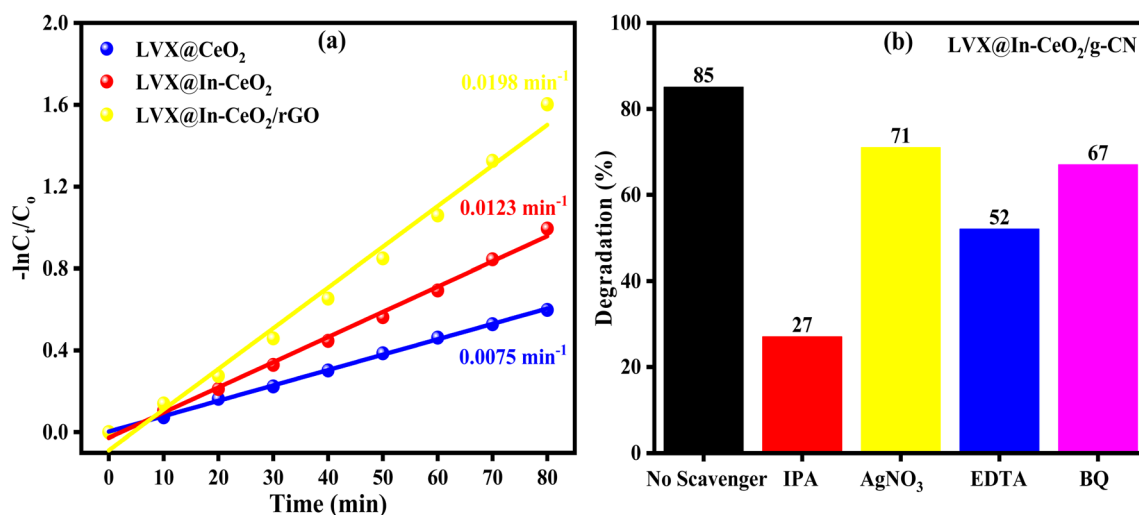


Fig. 7 (a) Kinetic studies of LVX degradation over CeO_2 , In-CeO_2 , and $\text{In-CeO}_2/\text{g-CN}$, and (b) scavenging studies over $\text{In-CeO}_2/\text{g-CN}$.



Table 1 Detailed comparison of the present work with previous studies

Sr. no.	Photocatalyst	Pollutant	Conditions	D(%)	References
1	Ag-doped g-CN/Biochar	Ciprofloxacin (CIP)	50 ppm CIP, 50 mg catalyst, visible-light, 4 h	70%	61
2	ZnO/g-CN	Methyl orange (MO)	10 ppm MO, 50 mg catalyst, 400 W lamp	83.71%	62
3	Ni-doped α -Fe ₂ O ₃ /g-CN	Ciprofloxacin (CIP)	10 mg per L CIP, 15 mg catalyst, solar light $\sim 660 \text{ Wm}^{-2}$	82.1%	63
4	g-CN/Bi ₂ O ₂ CO ₃	Carbamazepine (CBZ)	20 ppm CBZ, 1 g of catalyst, sunlight, 180 minutes	98%	64
5	ZnCr ₂ O ₄ /g-CN	Ciprofloxacin (CIP)	10 mg per L CIP, 75 mg of catalyst, Halogen lamp, 120 minutes	74.36%	65
6	Bi ₂ MoO ₆ /g-CN	Ciprofloxacin (CFX)	10 mg per L CFX, 0.05 g of catalyst, LED light, 90 minutes	89.04%	66
7	In-CeO ₂ /g-CN	Levofloxacin (LVX)	10 mg per L LVX, 50 mg catalyst, Xe lamp (300 W, UV cutoff filter $\lambda > 420 \text{ nm}$), and 80 minutes	85%	Present study

presence of IPA, the degradation dropped considerably. The scavenging investigation presents the contribution of active species in the order $e^- < h^+ < \cdot\text{O}_2^- < \text{HO}\cdot$ for LVX degradation. A detailed comparison of the present work with previous findings is presented in Table 1.

Electronic band structure alignment and energy band energies hold vital significance in designing heterojunction materials with a specific scheme for charge migration. To get insights into the mechanism of LVX degradation over In-CeO₂/g-CN, the energy band values, VB maxima (E_{VB}) and CB minima

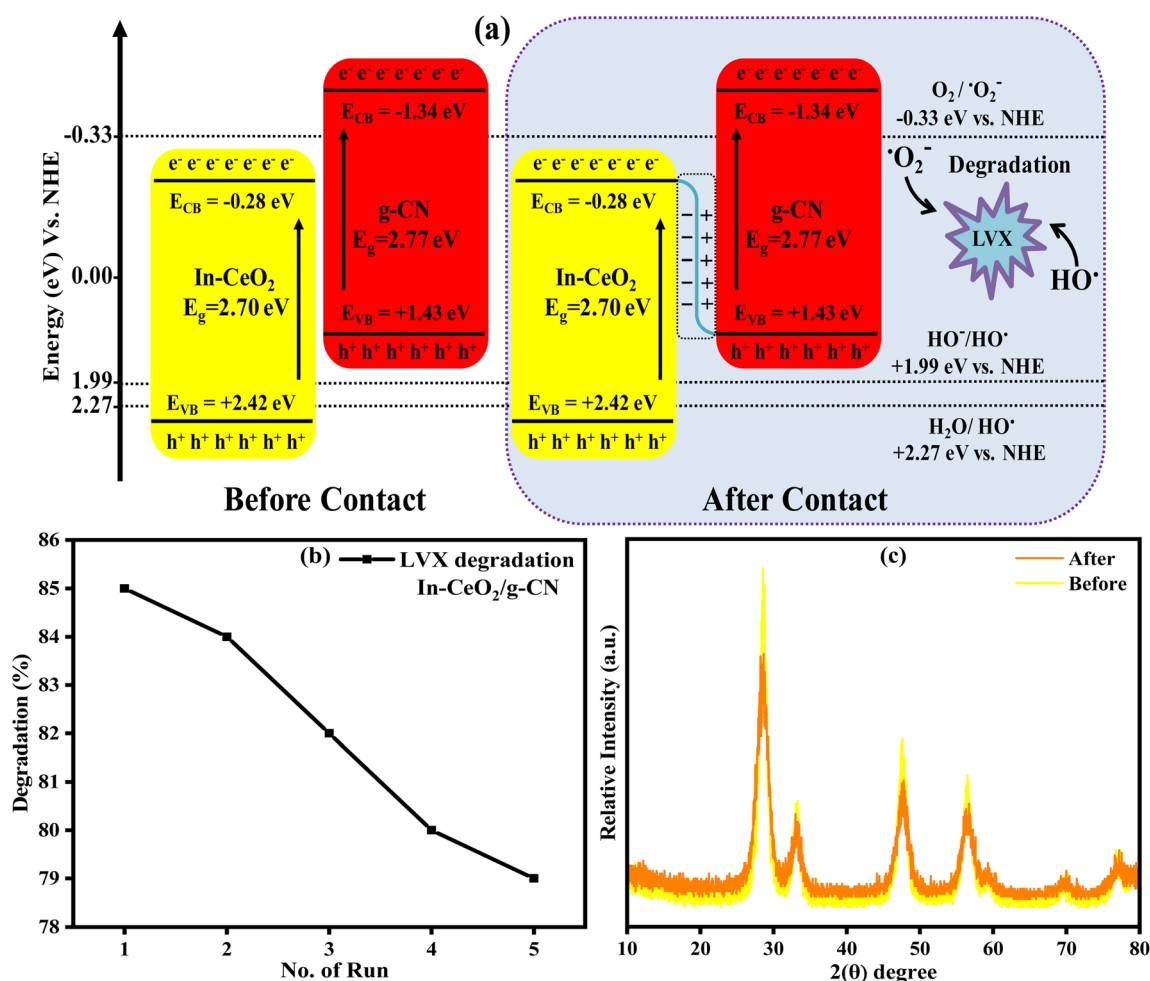


Fig. 8 (a) Schematic of the proposed S-scheme In-CeO₂/g-CN heterojunction and (b) reusability and (c) before-and-after XRD pattern alignments to study the stability of the catalyst.

(E_{CB}) of g-CN and In-CeO₂ were explored by applying the relations:^{67,68}

$$E_{CB} = \chi - E_e - 0.5 E_g$$

$$E_{VB} = E_{CB} + E_g$$

Here, “ χ ” is electronegativity, and $E_e = 4.5$ eV denotes the energy of a free electron on the hydrogen scale. The calculated energy band values were $E_{VB} = +2.42$ eV for In-CeO₂ and $E_{CB} = -0.28$ eV, while $E_{VB} = +1.43$ eV and $E_{CB} = -1.34$ eV for g-CN. Thermodynamically, pure In-CeO₂ is unable to generate ‘O₂^{•-} radicals due to E_{CB} being higher than the required reduction potential (O₂/O₂^{•-} = -0.33 eV vs. NHE,⁶⁹). Pure g-CN is unable to generate HO[•] radicals as it has an E_{VB} value lower than the required oxidation potential (HO[•]/HO^{•-} = 1.99 eV and H₂O/HO[•] = 2.23 eV vs. NHE,⁷⁰). But the scavenging studies reveal the generation of both ‘O₂^{•-} and HO[•] radicals, which degrade LVX. As shown in (Fig. 8), the low-redox-potential carriers, e⁻ of In-CeO₂ and h⁺ of g-CN, recombine, leaving behind the active e⁻ (g-CN) and h⁺ (In-CeO₂),^{71,72} which participate in the reduction and oxidation reactions producing active radical species that degrade LVX.

The reusability and structural stability of In-CeO₂/g-CN were studied by LVX degradation in different runs, and the results are presented in Fig. 8(b and c). The photocatalyst retains ~95% of its initial activity after multiple cycles, indicating good structural stability and recyclability; minor losses are likely due to insufficient catalyst recovery. The diffraction pattern of the recovered catalyst displays its structural stability, as no significant change was detected.

4. Conclusion

Pure CeO₂ and its indium-modified composition, In-CeO₂, were hydrothermally fabricated, while g-CN was synthesized through melamine calcination. The In-CeO₂ material was dispersed on g-CN through ultrasonication to construct the S-scheme In-CeO₂/g-CN heterojunction. XRD and FTIR analyses verified the formation of CeO₂, In-CeO₂, and In-CeO₂/g-CN, with thermal stability indicated by TGA. SEM micrographs showcased the dispersion of In-CeO₂, with g-CN preventing agglomeration. The In-CeO₂/g-CN heterojunction increased visible-light absorption under $\lambda > 420$ nm illumination and facilitated charge separation *via* band structure alignment, forming an S-scheme of charge migration. The PC efficiency was evaluated by LVX degradation in the presence of catalysts, CeO₂, In-CeO₂, and In-CeO₂/g-CN. The In-CeO₂/g-CN catalyst exhibited a maximum LVX degradation of 85% (0.0198 min⁻¹) compared to CeO₂ and In-CeO₂, which degraded LVX to an extent of 44% (0.0075 min⁻¹) and 63% (0.0123 min⁻¹), respectively. The formation of the In-CeO₂/g-CN S-scheme heterojunction enables the recombination of low-redox-potential charge carriers (with low redox ability), preventing active charge carriers (high redox ability) from recombining and making them available for photocatalytic reactions. Despite the improved activity, the study is limited to a single pollutant and

Xe-lamp illumination conditions; future work will evaluate performance under solar-simulated visible light and conduct advanced interfacial analyses such as XPS.

Author contributions

Mazen R. Alrahili (writing – original draft, validation), M. Abdel Rafea (funding acquisition, project administration, resources), Magdi E. A. Zaki (investigation, formal analysis), M. Khairy (data curation, validation), Mohamed. R. El-Aassar (investigation, data curation), Sultan Albarakati (software, methodology), Imran Shakir (visualization, formal analysis), Abdullah K. Alanazi (writing – review & editing), Muhammad Aadil (supervision).

Conflicts of interest

There are no conflicts to declare.

Data availability

Data will be available upon request.

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References

- 1 J. Zhang, X. Wang, X. Wang and C. Li, Heterophase junction effect on photogenerated charge separation in photocatalysis and photoelectrocatalysis, *Acc. Chem. Res.*, 2025, **58**, 787–798.
- 2 P. Swaminaathan, A. Saravanan, P. Yaashikaa and A. Vickram, Recent advances in photocatalytic degradation of persistent organic pollutants: Mechanisms, challenges, and modification strategies, *Sustain. Chem. Environ.*, 2024, **8**, 100171.
- 3 Y. Sari, P. L. Gareso, B. Armynah and D. Tahir, A review of TiO₂ photocatalyst for organic degradation and sustainable hydrogen energy production, *Int. J. Hydrogen Energy*, 2024, **55**, 984–996.
- 4 M.-A. Gatou, A. Syrrakou, N. Lagopati and E. A. Pavlatou, Photocatalytic TiO₂-based nanostructures as a promising material for diverse environmental applications: a review, *Reactions*, 2024, **5**, 135–194.
- 5 A. R. Bhapkar and S. Bhame, A review on ZnO and its modifications for photocatalytic degradation of prominent textile effluents: Synthesis, mechanisms, and future directions, *J. Environ. Chem. Eng.*, 2024, **12**, 112553.
- 6 N. T. T. Nguyen, A. N. Q. Phan, T. Van Tran and T. T. T. Nguyen, Morinda citrifolia fruit extract-mediated synthesis of ZnO and Ag/ZnO nanoparticles for photocatalytic degradation of tetracycline, *Environ. Res.*, 2025, **273**, 121209.



- 7 L. D. Sonawane, A. S. Mandawade, L. N. Bhoje, H. I. Ahemad, S. S. Tayade, Y. B. Aher, A. B. Gite, L. K. Nikam, S. D. Shinde and G. H. Jain, Sol-gel and hydrothermal synthesis of CeO₂ NPs: their physiochemical properties and applications for gas sensor with photocatalytic activities, *Inorg. Chem. Commun.*, 2024, **164**, 112313.
- 8 K. Sharma, S. Sonu, A. Sudhaik, T. Ahamad, S. Kaya, S. Thakur, Q. Van Le, V.-H. Nguyen, A. Singh and L. H. Nguyen, Mechanistic insights into the reaction pathway for efficient cationic dye photocatalytic degradation and the importance of the enhanced charge isolation over dual Z-scheme CeO₂/BiOCl/Ag₂WO₄ photocatalyst, *J. Water Proc. Eng.*, 2024, **66**, 105918.
- 9 J. Wang, X. Niu, Q. Hao, K. Zhang, X. Shi, L. Yang, H. Y. Yang, J. Ye and Y. Wu, Promoting charge separation in CuInS₂/CeO₂ photocatalysts by an S-scheme heterojunction for enhanced photocatalytic H₂ production, *Chem. Eng. J.*, 2024, **493**, 152534.
- 10 M. N. Shabbir, R. Alabada, M. Aadil, Z. Ahmad, A. A. Alothman, N. A. Almuhs, W. A. Khan and R. M. Mohamed, Synthesis, structural characterizations, and photocatalytic application of silver-doped indium oxide ceramic nanoparticles, *Ceram. Int.*, 2024, **50**, 4404–4414.
- 11 M. A. Hamza, A. El-Sayed, A. N. El-Shazly and M. G. Elmaghary, Efficient utilization of ceramic waste (cyclone dust waste) for enhancing the photocatalytic performance of TiO₂ nanoparticles toward Rhodamine B photodegradation, *J. Cleaner Prod.*, 2024, **434**, 140341.
- 12 L. Al-Hajji, A. Al-Anazi, A. A. Ismail, A. M. El-Toni, A. Khan and M. Shkir, A pn heterojunction PdO/CeO₂ photocatalysts with enhanced photocatalytic ability for reduction of Hg (II) ions from aqueous solution, *Ceram. Int.*, 2024, **50**, 45650–45657.
- 13 A. Rianjanu, K. D. P. Marpaung, C. Siburian, S. A. Muhtar, N. I. Khamidy, J. Widakdo, N. Yulianto, R. Aflaha, K. Triyana and T. Taher, Enhancement of photocatalytic activity of CeO₂ nanorods through lanthanum doping (La–CeO₂) for the degradation of Congo red dyes, *Results Eng.*, 2024, **23**, 102748.
- 14 S. R. A. Kumar, D. V. Mary, G. S. Josephine and A. Sivasamy, Hydrothermally synthesized WO₃: CeO₂ supported gC₃N₄ nanolayers for rapid photocatalytic degradation of azo dye under natural sunlight, *Inorg. Chem. Commun.*, 2024, **164**, 112366.
- 15 D. Yang, Q. Ye, C. Qu, F. Meng, L. Wang and Y. Li, Enhanced hydrogen evolution and tetracycline degradation by a Z-scheme g-C₃N₄ nanosheets loaded CeO₂ photocatalyst under visible light irradiation, *J. Environ. Chem. Eng.*, 2024, **12**, 112563.
- 16 H. Zhang, L. Bao, Y. Pan, J. Du and W. Wang, Interface reconstruction of MXene-Ti₃C₂ doped CeO₂ nanorods for remarked photocatalytic ammonia synthesis, *J. Colloid Interface Sci.*, 2024, **675**, 130–138.
- 17 M. C. Iannaco, S. Mottola, V. Vaiano, G. Iervolino and I. De Marco, CeO₂-CuO composites prepared via supercritical antisolvent precipitation for photocatalytic hydrogen production from lactic acid aqueous solution, *J. CO₂ Util.*, 2024, **85**, 102878.
- 18 Fauzia, M. A. Khan, M. Chaman and A. Azam, Antibacterial and sunlight-driven photocatalytic activity of graphene oxide conjugated CeO₂ nanoparticles, *Sci. Rep.*, 2024, **14**, 6606.
- 19 J. Naseem, M. A. Rafea, M. E. A. Zaki, M. I. Attia, M. R. El-Aassar, F. Alresheedi, S. Zulfiqar and M. Aadil, Combining nanotechnology and nanohybrid methods to improve the physical and chemical properties of CuS and boost its photocatalytic aptitude, *RSC Adv.*, 2025, **15**, 13940–13950.
- 20 S. Ali, H. Ali, S. H. Bakhtiar, S. Ali, M. Zahid, A. Ismail, P. M. Ismail, A. Zada, I. Khan and H. Shen, Bifunctional phosphate-modulated Cu₂O/CeO₂ redox heterojunction: a promising approach for proficient CO₂ reduction, *J. Alloys Compd.*, 2024, **972**, 172766.
- 21 V. Rajappa, S. Mohan, S. Bharathkumar, S. L. Rokhum, A. Fatehmulla, H. Valdes and R. Ilangovan, Fe, N Dual-Doped Cerium Oxide Photocatalyst Manifesting the Simultaneous Degradation of Dye–Heavy Metal Mixed Pollutants under Sunlight, *Ind. Eng. Chem. Res.*, 2024, **63**, 21760–21770.
- 22 L. Luo, R. Wang, T. Wang, J. Li, Y. Xiao, K. Qi, X. Guo, Z. Feng, J. Tang and F. Zhang, Coverage-Dependent Selective Conversion of Methane into Value-Added Ethane over Noble-Metal-Free Ni₁-CeO₂ Photocatalyst, *J. Am. Chem. Soc.*, 2025, **147**, 17566–17573.
- 23 Q. Liu, G. Tan, Y. Long, J. Wei, H. Tian, S. Xie and Y. Tang, In situ formation of CeO₂ coupled with hollow NiCo-LDH nanosheets for efficient photocatalytic hydrogen evolution, *Inorg. Chem. Front.*, 2024, **11**, 5080–5090.
- 24 A. Balapure, J. R. Dutta and R. Ganesan, Recent advances in semiconductor heterojunctions: a detailed review of the fundamentals of photocatalysis, charge transfer mechanism and materials, *RSC Appl. Interfaces*, 2024, **1**, 43–69.
- 25 Y. Liu, M. Li, T. Liu, Z. Wu and L. Zhang, Enhanced charge carrier transport in TiO₂/COF S-scheme heterojunction for efficient photocatalytic H₂O₂ production, *J. Mater. Sci. Technol.*, 2025, **233**, 201–209.
- 26 R. Kumar, A. Sudhaik, D. Kumar, R. Devi, E. Devi, A. Chawla, P. Raizada, C. M. Hussain, T. Ahamad and P. Singh, Synergistic photocatalytic activity of Bi₂O₃/g-C₃N₄/ZnO ternary heterojunction with dual Z-scheme charge transfer towards textile dye degradation, *J. Ind. Eng. Chem.*, 2025, **144**, 575–584.
- 27 H. Sun, L. Wang, X. Wang, Y. Dong, J. Ren, J. Xin, R. Jing and J. An, A novel WO₃/ZnIn₂S₄/CoWO₄ heterojunction for enhancement of photocatalytic degradation sparfloxacin: Dual S-scheme multi-charge transfer mode and Mechanistic pathway, *J. Environ. Chem. Eng.*, 2024, **12**, 112386.
- 28 Y.-H. Wu, Y.-Q. Yan, Y.-X. Deng, W.-Y. Huang, K. Yang and K.-Q. Lu, Rational construction of S-scheme CdS quantum dots/In₂O₃ hollow nanotubes heterojunction for enhanced photocatalytic H₂ evolution, *Chin. J. Catal.*, 2025, **70**, 333–340.



- 29 G. Arulprakash and R. Vijayaraghavan, Charge-separated 3D/2D layered heterojunction of NiNb₂O₆/E-gC₃N₄ as an efficient photocatalyst for photo-reduction of Cr⁶⁺ and photo-oxidation of dyes under visible and sunlight, *Appl. Surf. Sci.*, 2025, **684**, 161938.
- 30 M. Bilal, M. Q. Alfaifi, S. B. Ahmed, M. M. Abduljawad, Y. I. Alrashed, E. S. Aldurahim and Y. A. Alassmy, A review of strategies to switch heterojunction system from type-II to S-scheme for photocatalytic applications, *Mater. Sci. Semicond. Process.*, 2025, **186**, 109051.
- 31 B. Zhu, J. Sun, Y. Zhao, L. Zhang and J. Yu, Construction of 2D S-scheme heterojunction photocatalyst, *Adv. Mater.*, 2024, **36**, 2310600.
- 32 M. Aldrery, F. Alresheedi, M. R. El-Aassar, A. Ahmed, M. Aadil, A. Alazmi, A. El Jery, M. R. Alrahili and A. Amjad, Preparation and physicochemical characterization of highly efficient ZrO₂/g-C₃N₄ composite catalysts for visible-light-driven removal of tetracycline antibiotics, *Diamond Relat. Mater.*, 2025, **151**, 111801.
- 33 A. Majeed, S. Hassan, M. Zahra, I. Rafique, S. Iqbal, M. A. Shafiq, R. N. Qureshi, R. Akhtar, M. Rehan and M. A. R. Anjum, Mechanistic insights into the visible light photocatalytic activity of gC₃N₄/Bi₂O₃ composites for rhodamine B degradation and hexavalent chromium reduction, *RSC Adv.*, 2025, **15**, 16643–16653.
- 34 M. R. El-Aassar, H. M. A. Hassan, M. S. Alhumaimess, I. H. Alsohaimi, M. Alzaid, A. K. Alanazi, M. Algarni, S. Albarakati and M. Aadil, Synthesis of Nd/Ni co-doped LaFeO₃/g-C₃N₄ heterostructures for photocatalytic norfloxacin degradation, *Inorg. Chem. Commun.*, 2025, **182**, 115478.
- 35 A. Gandamalla, S. Manchala, P. Anand, Y.-P. Fu and V. Shanker, Development of versatile CdMoO₄/g-C₃N₄ nanocomposite for enhanced photoelectrochemical oxygen evolution reaction and photocatalytic dye degradation applications, *Mater. Today Chem.*, 2021, **19**, 100392.
- 36 P. Panchal, P. Rauwel, S. Sharma, S. Nehra, E. Estephan, K. Praakle, E. Rauwel, *Bio-Synthesis of Graphitic Carbon Nitride and ZnO/GCN Nanohybrid for Remarkable Environmental Application*, 2024.
- 37 G. Karthik, S. Mohan and R. G. Balakrishna, Ligand modulated charge transfers in Z-scheme configured Ni-MOF/g-C₃N₄ nanocomposites for photocatalytic remediation of dye-polluted water, *Sci. Rep.*, 2024, **14**, 26149.
- 38 A. Gandamalla, S. Manchala, A. Verma, Y.-P. Fu and V. Shanker, Microwave-assisted synthesis of ZnAl-LDH/g-C₃N₄ composite for degradation of antibiotic ciprofloxacin under visible-light illumination, *Chemosphere*, 2021, **283**, 131182.
- 39 K. M. Katubi, S. Jabeen, F. Tariq, A. Irshad, Z. Alrowaili, M. Al-Buriahi and M. F. Warsi, Harnessing advanced nanomaterials: wastewater treatment with sustainable approach using 2D g-C₃N₄ based Ho-doped LaCoO₃ nanocomposite, *Ceram. Int.*, 2024, **50**, 12415–12426.
- 40 K. Shafiq, M. Aadil, W. Hassan, Q. Choudhry, S. Gul, A. Rais, A. A. Fattah, K. H. Mahmoud and M. Z. Ansari, Cobalt and holmium co-doped nickel ferrite nanoparticles: synthesis, characterization and photocatalytic application studies, *Z. Phys. Chem.*, 2023, **237**, 1325–1344.
- 41 H. I. Ahemad, G. E. Patil, Y. B. Aher, M. S. Malik, L. D. Sonawane, M. A. More, A. S. Mandawade, D. Y. Patil, S. D. Shinde and G. H. Jain, Synthesis and characterization of CeO₂ nanoparticles using *Plectranthus barbatus* leaf extract and its CO gas sensing and antimicrobial activity, *Mater. Lett.*, 2025, **379**, 137652.
- 42 K. M. Katubi, A. Rasheed, A. Ihsan, B. Shaheen, Z. Alrowaili, M. Al-Buriahi, M. I. Din, I. Shakir and S. Munir, Neodymium-doped nickel cobaltite reinforced with 2D MXene nanocomposite (Nd-NiCo₂O₄/MXene) for enhanced photocatalytic degradation of the organic pollutants, *Opt. Mater.*, 2024, **152**, 115390.
- 43 X. Yu, X. Tang, H. Luo and Y. Mao, Construction of biochar assisted S-scheme of CeO₂/g-C₃N₄ with enhanced photoreduction CO₂ to CO activity and selectivity, *Mater. Res. Bull.*, 2025, **181**, 113085.
- 44 H. Somaily, Construction of g-CN/SnSe nanocomposite through a hydrothermal approach for enhanced OER study, *Ceram. Int.*, 2024, **50**, 33382–33391.
- 45 T. Fei, Performance and mechanism of constructed CuO/CeO₂ p-n heterojunction for photocatalytic degradation of methylene blue, *Trans. Nonferrous Met. Soc. China*, 2024, **34**, 1951–1964.
- 46 N. M. Ghazy, E. A. Ghaith, Y. Abou El-Reash, R. R. Zaky, W. M. Abou El-Maaty and F. S. Awad, Enhanced performance of hydroxyl and cyano group functionalized graphitic carbon nitride for efficient removal of crystal violet and methylene blue from wastewater, *RSC Adv.*, 2022, **12**, 35587–35597.
- 47 M. E. Ali, M. Abouelfadl, N. A. Badway and K. M. Salam, Effective removal of organic compounds using a novel cellulose acetate coated by PA/g-CN/Ag nanocomposite membranes, *Surf. Interfaces*, 2022, **29**, 101748.
- 48 A. Baishnisha, K. Divakaran, V. Balakumar, K. N. Perumal, C. Meenakshi and R. S. Kannan, Synthesis of highly efficient g-CN@CuO nanocomposite for photocatalytic degradation of phenol under visible light, *J. Alloys Compd.*, 2021, **886**, 161167.
- 49 N. AlMasoud, A. Irshad, U. Rafiq, T. S. Alomar, A. A. Alwallan, M. F. Warsi and Z. M. El-Bahy, Sol-gel synthesis of Tb-doped lithium-nickel ferrite anchored onto g-C₃N₄ sheets for efficient photocatalytic degradation of organic dyes, *Ceram. Int.*, 2024, **50**, 46892–46903.
- 50 M. Yusuf, F. M. Elfghi, S. A. Zaidi, E. C. Abdullah and M. A. Khan, Applications of graphene and its derivatives as an adsorbent for heavy metal and dye removal: a systematic and comprehensive overview, *RSC Adv.*, 2015, **5**, 50392–50420.
- 51 B. Huwaimel, K. M. Younes, A. S. Abouzied, S. A. Almahmoud, S. Alshehri, Z. M. El-Bahy and M. F. Warsi, Cerium-doped indium vanadate microspheres loaded onto the 2D conductive matrix for boosted photodegradation of persistent organic pollutants, *Ceram. Int.*, 2025, **51**, 12806–12817.



- 52 M. F. Abou Taleb and M. M. Ibrahim, Indium-doped tungsten oxide architectures anchored on 2D rGO Matrix with enhanced visible-light-response and efficient charge separation for photocatalytic degradation of organic pollutants, *J. Alloys Compd.*, 2024, **1003**, 175628.
- 53 L. Xu, P. Guo, J. Xu, B. Shen and Z. Zhao, Regulation of TiO₂/ZSM-5 catalyst for enhanced photocatalytic toluene oxidation: Intensified light absorption, charge separation and toluene adsorption, *Colloids Surf., A*, 2024, **690**, 133832.
- 54 A. Rasheed, I. Bibi, F. Majid, S. Kamal, B. Taj, M. Raza, N. Khaliq, K. M. Katubi, S. Ezzine and N. Alwadai, Mn doped SrFe₂O₁₉ fabricated via facile microemulsion route and solar-light-driven photocatalytic removal of crystal violet dye, *Phys. B*, 2022, **646**, 414303.
- 55 S. Baqi, M. T. Oo and F. C. C. Ling, Unveiling the impact of Cu doping on charge carrier density and transfer in ZnO/ZnSe heterojunctions for PEC applications, *Mater. Sci. Semicond. Process.*, 2025, **198**, 109780.
- 56 K. Kalidasan, S. Mallapur and S. G. Kumar, Pivotal role of surface and bulk Gd species in WO₃ to promote Type-II charge carrier transfer pathways in Gd-WO₃/g-C₃N₄ heterojunction photocatalyst, *J. Environ. Chem. Eng.*, 2024, **12**, 113054.
- 57 K. K. Das, U. A. Mohanty, R. Mohanty, P. P. Sarangi, D. P. Sahoo and K. Parida, Improving charge carrier separation through S-scheme-based 2D-2D WS₂/sulfur-doped g-C₃N₄ heterojunctions for a superior photocatalytic O₂ reduction reaction, *ACS Appl. Energy Mater.*, 2024, **7**, 6360–6375.
- 58 M. Yi, Y. Ren, X. Zhang, Z. Zhu and J. Zhang, Ionic liquid-assisted synthesis of N, F, and B co-doped BiOBr/Bi₂Se₃ on Mo₂CTx for enhanced performance in hydrogen evolution reaction and supercapacitors, *J. Colloid Interface Sci.*, 2024, **658**, 334–342.
- 59 L. Shuai, L. Tian, X. Huang, J. Dou, J. Yu and X. Chen, Enhanced charge carrier separation and stable photoelectrochemical water splitting via a high-performance BiVO₄/BiOBr Type-II heterojunction, *Int. J. Hydrogen Energy*, 2024, **88**, 19–28.
- 60 G. Zheng, S. Jiang, M. Cai, F. Zhang and H. Yu, WO₃/FeOOH heterojunction for improved charge carrier separation and efficient photoelectrochemical water splitting, *J. Alloys Compd.*, 2024, **981**, 173637.
- 61 I. Idrees, M. Zafar, M. A. Umer, F. Rehman, A. Razzaq, S. Kim, Y. Yang and W. Y. Kim, Silver (Ag) doped graphitic carbon nitride (g-C₃N₄)/biochar composite photocatalyst for improved photocatalytic degradation of ciprofloxacin (CIP), *Results Phys.*, 2025, **68**, 108071.
- 62 A. H. Warda, M. Rostom, M. I. Mashaly, E. T. Helmy, E. A. Gomaa and E. M. AbouElleef, Facile and eco-friendly synthesis of GCN/ZnO nanocomposites for enhanced photocatalytic, antimicrobial and antioxidant activities: applications in biomedicine and wastewater treatment, *Surf. Interfaces*, 2025, 107123.
- 63 C. N. Lakshmi, M. Irfan, R. Sinha and N. Singh, Magnetically recoverable Ni-doped iron oxide/graphitic carbon nitride nanocomposites for the improved photocatalytic degradation of ciprofloxacin: Investigation of degradation pathways, *Environ. Res.*, 2024, **242**, 117812.
- 64 J. U. R. Abbasi, K. H. Leong, L. C. Sim, C. Dai, A. A. Aziz, S. Sethupathi and S. Ibrahim, Amalgamation of g-C₃N₄/Bi₂O₂CO₃ heterojunction composites for enhanced sunlight photocatalytic removal of carbamazepine, *Environ. Sci. Pollut. Res.*, 2025, 1–14.
- 65 R. R. Chandrapal, K. Bharathi, G. Bakiyaraj, S. Bharathkumar, Y. Priyajanani, S. Manivannan, J. Archana and M. Navaneethan, Harnessing ZnCr₂O₄/g-C₃N₄ nanosheet heterojunction for enhanced photocatalytic degradation of rhodamine B and ciprofloxacin, *Chemosphere*, 2024, **350**, 141094.
- 66 P. T. Le, T. P. Nguyen, H. N. Nguyen, T. H. Tran, T. H. Do, P. T. Thuy, T. M. T. Dinh, T. Tsubota, V. D. Nguyen and T. D. Nguyen, Z-scheme Bi₂MoO₆/g-C₃N₄ heterojunction for efficient antibiotic degradation via persulfate activation under visible light, *Water Sci. Eng.*, 2025, **18**(4), 515–526.
- 67 P. Vijayarengan, S. C. Panchangam, A. Stephen, G. Bernatsha, G. K. Murali, S. S. Loka, S. K. Manoharan, V. Vemula, R. R. Karri and G. Ravindran, Highly efficient visible light active iron oxide-based photocatalysts for both hydrogen production and dye degradation, *Sci. Rep.*, 2024, **14**, 18299.
- 68 L. Zhao, J. Li, J. Shao, L. Zhang, Y. Ji, X. Li and D. Ju, Antimicrobial studies of visible light-responsive nanoflower spheres Bi₂WO₆/ZnO, *Ceram. Int.*, 2024, **50**, 48948–48966.
- 69 W. Miao, W. He, L. Shen, Y. Li, Z. Fang, Z. Yang and G. Kai, Nitrogen-oxygen defect engineering enhanced intrinsic electric field in CoFe₂O₄/g-C₃N₄ heterojunctions for photocatalytic tetracycline degradation and H₂ evolution, *J. Environ. Chem. Eng.*, 2024, **12**, 114202.
- 70 Q. Wang, C. Yao, X. Liu, J. Qiu, R. Wang, J. Liu and W. Wang, 1D rod-like {220}-faceted CeO₂/ZnO S-scheme heterojunctions: design, photocatalytic mechanism and DFT calculations, *J. Mater. Chem. A*, 2024, **12**, 24441–24458.
- 71 L. Zhang, J. Zhang, J. Yu and H. García, Charge-transfer dynamics in S-scheme photocatalyst, *Nat. Rev. Chem.*, 2025, 1–15.
- 72 M. Gu, Y. Yang, B. Cheng, L. Zhang, P. Xiao and T. Chen, Unveiling product selectivity in S-scheme heterojunctions: Harnessing charge separation for tailored photocatalytic oxidation, *Chin. J. Catal.*, 2024, **59**, 185–194.

