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Chemical routes to materials

Sustainable green approach of simple hydrothermal treatment of g-C_3N_4 to boost the CO_2 conversion into methanol through photoelectrocatalysis

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ABSTRACT

The carbon dioxide (CO_2) transformation into beneficial fuels or chemicals by photoelectrocatalytic (PeC) reaction has been proved sustainable. As a standalone or component in composites, the graphitic carbon nitride (g-C_3N_4) catalysts were significantly utilized for PeC approaches. In this research work, as a first instance, a sustainable green approach of simple hydrothermal treatment at various temperatures, such as 90, 120, 150, and 180 °C, was adopted to synthesize g-C_3N_4 (xgCN) catalysts to enrich their PeC CO_2 reduction into methanol activity. The simple hydrothermal treatment achieved increased stacking layer distance of g-C_3N_4 and fine-tuning of the band gap. The 120gCN catalyst (treated at 120 °C) exhibited a superior current at − 1.0 V of 3.62 mA cm^{-2} and a 4.39 µmol L^{-1} h^{-1} cm^{-2} methanol generation in PeC CO_2 reduction reaction, which was around twofold superior compared to that of PgCN (untreated g-C_3N_4) catalyst. The excellent efficiency of the 120gCN catalyst was credited to its better production and lesser electron (e^-)-hole (h^+) pairs recombination rate.

Introduction

Developing efficient catalysts for photocatalytic (PC) and/or photoelectrocatalytic (PeC) energy conversion or utilization for valuable works has gained extensive research interest because of their assistance in addressing the world's energy and environmental issues [1–3]. Different types of photocatalysts, including those based on metal oxides, metal–organic frameworks, graphitic carbon nitride (g-C_3N_4), composites, etc.,

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have been demonstrated for photocatalytic environmental decontamination and other energy applications [4–7]. For the sustainable carbon dioxide (CO_2) conversion into useful products, the PeC process, which involves both PC and electrocatalytic principles, has been proved to be a constructive method [8]. Nevertheless, several new types of photocatalysts have been explored in recent decades, and the efficiency enhancement of promising existing photocatalytic materials remains essential [9–11]. g-C_3N_4, the semiconductor of non-metal type, has been widely studied for several PC and PeC applications, which include organic compound transformations, degradation of pollutants, hydrogen generation, and so on [12, 13]. The g-C_3N_4, having graphitic-like morphology, has played a remarkable role in composite catalysts for achieving significant performances for PC or PeC efficiencies [14, 15], including for the CO_2 conversion into value-added products [16–18].

The properties, for example, good stability, appropriate band edge positions and band gap, and easy preparation methods, have gained additional superiority of the g-C_3N_4 [19]. Besides its significant performance as a standalone catalyst and as a component in composite materials, the fast electron (e^-)-hole (h^+) pairs recombination and the heavy agglomeration layers nature of the bulk g-C_3N_4 are detrimental to efficient PeC activities [20]. Many methods, such as coupling with another semiconductor [16], doping with elements [21, 22], and so on, were attempted to increase the g-C_3N_4 performances. However, the composite catalysts' performance could still be better [17, 23]. The potential improvement of pristine g-C_3N_4 should be explored as it is a key building block for many potential catalytic materials. Several types of treatment of pristine g-C_3N_4, such as sonication at higher temperatures with organic solvents [24], sonication at room temperature with water [25], and treatment with a solution of NaOH [26], have been reported to improve their efficiencies. However, the above procedures involve harsh conditions and some chemicals, which can be considered non-environmentally friendly. Therefore, the significant problems of pristine g-C_3N_4, such as rapid charge recombination, increased agglomeration layers, and a non-environmentally friendly synthesis treatment route, should be addressed. Also, PeC enhancement of pristine g-C_3N_4 for converting CO_2 into valuable chemicals or fuels has not been explored so far. However, a variety of methods, such as doping with heteroatoms, deposition of cocatalysts, and formation of composites, have been widely employed to improve the PeC CO_2 reduction performances of g-C_3N_4 catalysts; these methods involve complex synthetic routes and utilize harsh chemical conditions. Therefore, it remains challenging to enhance the charge separation and transfer behavior of the neat g-C_3N_4 to achieve better PeC CO_2 reduction activities. Particularly, the role of simple and dopant-free modification of g-C_3N_4 to improve selective PeC CO_2 reduction into methanol has not been investigated systematically.

Herein, for the first time, we demonstrate a sustainable green approach using simple hydrothermal treatment at various temperatures to prepare g-C_3N_4 (xgCN) catalysts and their enhanced PeC CO_2 reduction into methanol. In addition to its environmental compatibility, this strategy enables the controlled modification of neat g-C_3N_4 without using or adding any additional chemical components, thus providing a clear correlation between structure and property performance. This work hence revealed fundamental insight into how mild structural modification of neat g-C_3N_4 improved charge separation and transfer behavior, and PeC CO_2 reduction performances. The hydrothermal treatment conditions of g-C_3N_4 play a crucial role in the PC and PeC activity of the catalysts [24–28]. Sano et al. demonstrated the significantly improved morphological and PC NO oxidation properties of g-C_3N_4 by hydrothermal treatment in the range from 90 to 150 °C [26]. Zhai et al. reported that higher hydrothermal treatment conditions, ranging from 250 to 300 °C, improved the morphological and PC properties of g-C_3N_4; however, partial decomposition of g-C_3N_4 occurred at higher temperatures [27]. Ming et al. also demonstrated that the mild hydrothermal treatment temperature of the oxidized g-C_3N_4 improved the photocurrent generation activity by around ten times [28]. Therefore, to systematically study the effects of hydrothermal conditions on the structural, electrical, and PeC CO_2 reduction properties of xgCN, we selected a range of treatment temperatures (mild, mid, and relatively high) such as 90, 120, 150, and 180 °C. The UV-DRS and XRD results showed the fine-tuning of the band gap and increased stacking layer distance of g-C_3N_4 on mild hydrothermal treatment, respectively. The PeC CO_2 reduction activity of 120gCN catalyst (hydrothermally treated at 120 °C) showed twofold superior photocurrent density and methanol generation compared to the PgCN (as-prepared). The exceptional activity of the 120gCN bulk g-C_3N_4 was demonstrated by the B-doped g-C_3N_4 catalyst developed using an ultrasonic-assisted process. The improved performance was attributed to the isolation of charges and increased charge transportation potential of the catalyst [53]. Similarly, C-doped g-C_3N_4 catalyst prepared by a double-stage polymerization procedure showed 4.6-fold higher PC CO_2 reduction to CO compared to the pure g-C_3N_4 owing to its higher generation and effective trapping of e^- and h^+ [54]. The reports in Table 1 [47–54], which employ acid modification, heteroatom doping, multistep polymerization, and coupling with other components, are not considered sustainable because they use toxic chemicals and harsh experimental conditions to synthesize the catalysts. Additionally, the PeC process was rarely adopted for converting CO_2. Thus, the adopted sustainable green approach resulted in higher photogeneration and reduced recombination of pairs of e^--h^+ and showed around twofold greater reduction activity of PeC CO_2 to methanol than that of untreated g-C_3N_4. From a sustainability outlook, the hydrothermal treatment strategy employed in this work eliminates the utilization of any toxic chemicals as dopants or solvents, or high value metals which are generally used to improve the activity of g-C_3N_4 in the literature. Therefore, this approach can be considered as simple and environmentally friendly. Besides, it should also be noted that the methanol yield efficiency observed in the current research work is comparable with the reported g-C_3N_4-based catalysts synthesized using toxic chemicals and harsh experimental conditions. Therefore, the current simple and green approach represents a trade-off as the achievement of enhanced activity with reduced complex synthetic route and environmental impact. Additionally, the g-C_3N_4 synthesized using a water and thermal treatment procedure in a range of 90 to 180 °C can be considered a scalable and eco-friendly PeC CO_2 conversion pathway. This work may help bridge the gap between high productivity and sustainability by applying this simple and green approach with other promising catalysts or interface engineering to develop an alternative potential catalyst.

Conclusion

A sustainable green approach of the simple hydrothermal process without using any chemicals was adopted to treat the as-prepared g-C_3N_4 under different temperatures such as 90, 120, 150, and 180 °C. The low angle shifts in the XRD peak revealed the increased stacking layer distance of the hydrothermally treated g-C_3N_4 catalysts (xgCN), which was verified using the microscopic images of agglomerated sheet structure of PgCN and sheet structures of xgCN samples. The fine-tuning of the band gap and suppressed rate of recombination of e^--h^+ of xgCN catalysts were confirmed using the UV–Vis DRS (optical absorption) and PL results, correspondingly. Therefore, refined PeC CO_2 conversion into methanol formation activity was demonstrated over some of the prepared xgCN photocathodes. The 120gCN possessed a 3.62 mA cm^{-2} of superior photocurrent density among all the prepared catalysts, which was around two times enhanced than the PgCN (untreated g-C_3N_4) photocathode. Similarly, a superior of 4.39 μmol L^{-1} h^{-1} cm^{-2} of methanol generation from PeC CO_2 reduction was attained using the 120gCN compared to the other photocathodes, twofold higher than the PgCN. The superior performance of 120gCN catalyst was recognized to their improved photogeneration and suppressed recombination rate of e^--h^+ pairs. Hence, this work demonstrated the enhancement of methanol generation through the PeC reduction of CO_2 and fine-tuning of optical and morphological parameters of the g-C_3N_4 (as-prepared) by a sustainable green approach of an effortless mild hydrothermal treatment.

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Author contributions

Komatireddy DamodarReddy was involved in methodology, data curation, investigation, writing—original draft, and writing—review and editing. Prabhu Saravanan took part in methodology, conceptualization, investigation, writing—review and editing, writing—original draft, funding acquisition, and formal analysis. Pavan. P. Gotipamul participated in data curation and writing—review and editing. Cristian H. Campos was responsible for methodology, formal analysis, conceptualization, and writing—review and editing. Aravindhan Selvaraj contributed to investigation and writing—review and editing. Siva Chidambaram was responsible for investigation, conceptualization, writing—original draft, and writing—review and editing.

Data availability

The data can be made available on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval Not applicable.

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References

[1] Honnappa B, Ganesan S, Kokulnathan T, Palaniappan A, Sekar K (2025) Advances and challenges in photo/electrocatalytic seawater splitting for sustainable hydrogen production: a comprehensive review. Int J Hydrogen Energy 120:642–681. https://doi.org/10.1016/j.ijhydene.2025.03.168

[2] Poonia K, Singh P, Singh A, Thakur S, Van Le Q, Ahamad T, Raizada P, Wang C, Nguyen LH, Nguyen VH (2023) Photoelectrocatalytic systems for simultaneous energy recovery and wastewater treatment: a review. Environ Chem Lett 21:265–283. https://doi.org/10.1007/s10311-022-01514-w

[3] Liu L, Zhang Y, Huang H (2021) Junction engineering for photocatalytic and photoelectrocatalytic CO_2 reduction. Sol RRL. https://doi.org/10.1002/solr.202000430

[4] Thennarasu G, Rajendran S, Kalairaj A, Rathore HS, Panda RC, Senthilvelan T (2025) A comprehensive review on the application of semiconductor nanometal oxides photocatalyst for the treatment of wastewater. Clean Technol Environ Policy 27:495–516. https://doi.org/10.1007/s10098-024-02960-6

[5] Salman M, Zhou H, Ahmed S, Ji Z, Shen X, Khan A, Yaseen W (2025) 2D metal-organic frameworks and their composites for water splitting: catalytic insights, synthesis pathways, and structural engineering strategies. Coord Chem Rev 544:216985. https://doi.org/10.1016/j.ccr.2025.216985

[6] Imran M, Abutaleb A, Ashraf Ali M, Ahamad T, Rahman Ansari A, Shariq M, Lolla D, Khan A (2020) UV light enabled photocatalytic activity of α-Fe_2O_3 nanoparticles synthesized via phase transformation. Mater Lett 258:126748. https://doi.org/10.1016/j.matlet.2019.126748

[7] Tofil HM, Ghazi R, Ghaib FA, Dara RN, Kebaili I, Boukhris I, Ding H, Rehman Z (2025) Modified g-C_3N_4 photocatalysts for clean energy and environmental applications: a review. Sustain Energy Fuels 9:2900–2927. https://doi.org/10.1039/D4SE01620C

[8] Zhang X, Wang J, Liu Y, Sun J, Xu B, Li T (2024) Photoelectrocatalytic reduction of CO_2 to CO via Cu_2O/C/PTFE nanowires photocathodes. ChemPhotoChem. https://doi.org/10.1002/cptc.202400005

[9] Murgolo S, De Ceglie C, Di Iaconi C, Mascolo G (2021) Novel TiO_2-based catalysts employed in photocatalysis and photoelectrocatalysis for effective degradation of pharmaceuticals (PhACs) in water: a short review. Current Opinion Green Sustain Chem 30:100473. https://doi.org/10.1016/j.cogsc.2021.100473

[10] Zhou Y, Chai Y, Sun H, Li X, Liu X, Liang Y, Gong X, Wu Z, Liu C, Qin P (2023) Design strategies and mechanisms of g–C_3N_4–based photoanodes for photoelectrocatalytic degradation of organic pollutants in water. J Environ Manage 344:118545. https://doi.org/10.1016/j.jenvman.2023.118545

[11] Rajput RB, Shaikh R, Sawant J, Kale RB (2022) Recent developments in ZnO-based heterostructures as photoelectrocatalysts for wastewater treatment: a review. Environ Adv 9:100264. https://doi.org/10.1016/j.envadv.2022.100264

[12] Bhanderi D, Lakhani P, Modi CK (2024) Graphitic carbon nitride (g-C_3N_4) as an emerging photocatalyst for sustainable environmental applications: a comprehensive review. RSC Sustain 2:265–287. https://doi.org/10.1039/D3SU00382E

[13] Saravanan P, Elangovan K, Campos CH, Sanhueza-Gómez F, Annamalai P, Ramakrishnan K, Mangalaraja RV (2023) Aerogels and carbon-based materials for photoelectrocatalytic CO_2 reduction into solar fuels. In: Cremades Ana, Maestre David (eds) Materials technology for the energy and environmental nexus, 2nd edn. IOP Publishing, Bristol

[14] Song X-L, Chen L, Ren J-T, Gao L-J, Yuan Z-Y (2024) Engineering of g-C_3N_4-based composites for photocatalytic and electrocatalytic water splitting: recent progress,

challenges and perspective. Coord Chem Rev 507:215752. https://doi.org/10.1016/j.ccr.2024.215752

[15] Du Q, Zhang H, Jiang Z, Xiong K, Yang Q, Yang N, Song Y, Chen J (2023) Structural and chemical approaches to enhance the photo/electrocatalytic performance of carbon/g-C_3N_4 composite materials. Chem Commun 59:8476–8487. https://doi.org/10.1039/D3CC01511D

[16] Tang J, Guo C, Wang T, Cheng X, Huo L, Zhang X, Huang C, Major Z, Xu Y (2024) A review of g-C_3N_4 -based photocatalytic materials for photocatalytic CO_2 reduction. Carbon Neutralization 3:557–583. https://doi.org/10.1002/cnl2.121

[17] Saravanan P, Gotipamul PP, DamodarReddy K, Campos CH, Selvaraj A, Mangalaraja RV, Chidambaram S (2024) Synthesis of isolated ZnO nanorods on introducing g-C_3N_4 for improved photoelectrocatalytic methanol production by CO_2 reduction. Inorg Chem Commun 170:113313. https://doi.org/10.1016/j.inoche.2024.113313

[18] Jiang XX, De Hu X, Tarek M, Saravanan P, Alqadhi R, Chin SY, Rahman Khan MM (2020) Tailoring the properties of g-C3N4with CuO for enhanced photoelectrocatalytic CO2 reduction to methanol. J CO2 Util 40:101222. https://doi.org/10.1016/j.jcou.2020.101222

[19] Hayat A, Sohail M, El Jery A, Al-Zaydi KM, Alshammari KF, Khan J, Ali H, Ajmal Z, Taha TA, Ud Din I, Altamimi R, Hussein MA, Al-Hadeethi Y, Orooji Y, Ansari MZ (2023) Different Dimensionalities, Morphological Advancements and Engineering of g-C_3N_4 -Based Nanomaterials for Energy Conversion and Storage. Chem Rec. https://doi.org/10.1002/tcr.202200171

[20] Fan C, Miao J, Xu G, Liu J, Lv J, Wu Y (2017) Graphitic carbon nitride nanosheets obtained by liquid stripping as efficient photocatalysts under visible light. RSC Adv 7:37185–37193. https://doi.org/10.1039/C7RA05732F

[21] Wang H, Zhang X, Xie J, Zhang J, Ma P, Pan B, Xie Y (2015) Structural distortion in graphitic-C_3N_4 realizing an efficient photoreactivity. Nanoscale 7:5152–5156. https://doi.org/10.1039/C4NR07645A

[22] Zhu M, Zhai C, Sun M, Hu Y, Yan B, Du Y (2017) Ultrathin graphitic C_3N_4 nanosheet as a promising visible-light-activated support for boosting photoelectrocatalytic methanol oxidation. Appl Catal B Environ 203:108–115. https://doi.org/10.1016/j.apcatb.2016.10.012

[23] Zhang P, Li N, Li L, Yu Y, Tuerhong R, Su X, Zhang B, Han L, Han Y (2024) G-C3N4-based photocatalytic materials for converting CO_2 into energy: a review. ChemPhysChem. https://doi.org/10.1002/cphc.202400075

[24] Zhao H, Yu H, Quan X, Chen S, Zhang Y, Zhao H, Wang H (2014) Fabrication of atomic single layer graphitic-C_3N_4 and its high performance of photocatalytic disinfection under visible light irradiation. Appl Catal B Environ 152:46–50. https://doi.org/10.1016/j.apcatb.2014.01.023

[25] Zhang X, Xie X, Wang H, Zhang J, Pan B, Xie Y (2013) Enhanced photoresponsive ultrathin graphitic-phase C_3N_4 nanosheets for bioimaging. J Am Chem Soc 135:18–21. https://doi.org/10.1021/ja308249k

[26] Sano T, Tsutsui S, Koike K, Hirakawa T, Teramoto Y, Negishi N, Takeuchi K (2013) Activation of graphitic carbon nitride (g-C_3N_4) by alkaline hydrothermal treatment for photocatalytic NO oxidation in gas phase. J Mater Chem A 1:6489. https://doi.org/10.1039/c3ta10472a

[27] Zhai B, Li Y, Jiang Y, Mao L, Shi J, Zhao Q, Bin Z, Wang F, Du Y, Jin H (2025) High-temperature continuous hydrothermal post treatment derived g-C_3N_4 for enhanced photocatalytic H_2 production. J Colloid Interface Sci 685:1099–1108. https://doi.org/10.1016/j.jcis.2025.01.195

[28] Ming L, Yue H, Xu L, Chen F (2014) Hydrothermal synthesis of oxidized g-C_3N_4 and its regulation of photocatalytic activity. J Mater Chem A 2:19145–19149. https://doi.org/10.1039/C4TA04041D

[29] Ganesan S, Kokulnathan T, Sumathi S, Palaniappan A (2024) Efficient photocatalytic degradation of textile dye pollutants using thermally exfoliated graphitic carbon nitride (TE–g–C_3N_4). Sci Rep 14:2284. https://doi.org/10.1038/s41598-024-52688-y

[30] Hassanzadeh-Tabrizi SA, Mohamad Shahi D (2023) Synthesis of W/Fe co-doped g-C_3N_4 decorated with Au nanoparticles for photocatalytic performance. Diam Relat Mater 134:109791. https://doi.org/10.1016/j.diamond.2023.109791

[31] Wang Q, Li Y, Huang F, Song S, Ai G, Xin X, Zhao B, Zheng Y, Zhang Z (2023) Recent advances in g-C_3N_4-based materials and their application in energy and environmental sustainability. Molecules 28:432. https://doi.org/10.3390/molecules28010432

[32] Wang H, Guan Y, Hu S, Pei Y, Ma W, Fan Z (2019) Hydrothermal synthesis of band gap-tunable oxygen-doped g-C_3N_4 with outstanding "two-channel" photocatalytic H_2O_2 production ability assisted by dissolution–precipitation process. NANO 14:1950023. https://doi.org/10.1142/S1793292019500231

[33] Hoang TVA, Nguyen PA, Choi WM, Shin EW (2022) The growth of extended melem units on g-C_3N_4 by hydrothermal treatment and its effect on photocatalytic activity of g-C_3N_4 for photodegradation of tetracycline hydrochloride under visible light irradiation. Nanomaterials 12:2945. https://doi.org/10.3390/nano12172945

[34] Xu C, Qiu P, Chen H, Jiang F (2020) Semi-crystalline graphitic carbon nitride with midgap states for efficient

photocatalytic nitrogen fixation. Appl Surf Sci 529:147088. https://doi.org/10.1016/j.apsusc.2020.147088

[35] Kumar S, Choudhary RB (2023) FRET mechanism of SnO_2 integrated luminescent g-C_3N_4 nanocomposite and its robust chemical, optical and thermal states for emissive layer application. J Inorg Organomet Polym Mater 33:599–610. https://doi.org/10.1007/s10904-022-02524-5

[36] Dias EM, Christoforidis KC, Francàs L, Petit C (2018) Tuning thermally treated graphitic carbon nitride for H_2 evolution and CO_2 photoreduction: the effects of material properties and mid-gap states. ACS Appl Energy Mater 1:6524–6534. https://doi.org/10.1021/acsaem.8b01441

[37] Shen M, Zhang L, Wang M, Tian J, Jin X, Guo L, Wang L, Shi J (2019) Carbon-vacancy modified graphitic carbon nitride: enhanced CO_2 photocatalytic reduction performance and mechanism probing. J Mater Chem A 7:1556–1563. https://doi.org/10.1039/C8TA09302D

[38] Zhang Q, Yin Y, Qi Y, Wu Y, Dove MT, Tan L, Huang H (2026) Enhanced g-C_3N_4 photocatalysis by high pressure and high temperature treatment: structural and mechanistic insights. Appl Surf Sci 716:164575. https://doi.org/10.1016/j.apsusc.2025.164575

[39] Dai Y, Sun Y, Yao J, Ling D, Wang Y, Long H, Wang X, Lin B, Zeng TH, Sun Y (2014) Graphene-wrapped TiO_2 nanofibers with effective interfacial coupling as ultrafast electron transfer bridges in novel photoanodes. J Mater Chem A 2:1060–1067. https://doi.org/10.1039/C3TA13399K

[40] Prabhu S, Cindrella L, Kwon OJ, Mohanraju K (2018) Photoelectrochemical and photocatalytic activity of TiO_2-WO_3 heterostructures boosted by mutual interaction. Mater Sci Semicond Process 88:10–19. https://doi.org/10.1016/j.mssp.2018.07.028

[41] Iqbal N, Afzal A, Khan I, Khan MS, Qurashi A (2021) Molybdenum impregnated g-C_3N_4 nanotubes as potentially active photocatalyst for renewable energy applications. Sci Rep 11:16886. https://doi.org/10.1038/s41598-021-96490-6

[42] Wu X, Chen F, Wang X, Yu H (2018) In situ one-step hydrothermal synthesis of oxygen-containing groups-modified g-C3N4 for the improved photocatalytic H2-evolution performance. Appl Surf Sci 427:645–653. https://doi.org/10.1016/j.apsusc.2017.08.050

[43] Hoang TVA, Nguyen PA, Shin EW (2023) Effect of morphological modification over g-C_3N_4 on photocatalytic hydrogen evolution performance of g-C_3N_4-Pt photocatalysts. Catalysts 13:92. https://doi.org/10.3390/catal13010092

[44] Wang J, Yang Z, Yao W, Gao X, Tao D (2018) Defects modified in the exfoliation of g-C_3N_4 nanosheets via a self-assembly process for improved hydrogen evolution performance. Appl Catal B Environ 238:629–637. https://doi.org/10.1016/j.apcatb.2018.07.017

[45] Zhao X, Yu J, Meng T, Luo Y, Fu Y, Li Z, Tian L, Sun L, Li J (2024) Modulation of the microstructure and enhancement of the photocatalytic performance of g-C_3N_4 by thermal exfoliation. Bull Chem React Eng Catal 19:442–454. https://doi.org/10.9767/bcrec.20189

[46] Todorova N, Papailias I, Giannakopoulou T, Ioannidis N, Boukos N, Dallas P, Edelmannová M, Reli M, Kočí K, Trapalis C (2020) Photocatalytic H_2 evolution, CO_2 reduction, and NO_x oxidation by highly exfoliated g-C3N4. Catalysts 10:1147. https://doi.org/10.3390/catal10101147

[47] Atta MR, Shaharun MS, Khan MMR, Al-Mahmodi AF, Almashwali AA, Bangash I (2024) ZIF-67 hybridization and boron doping to enhance the photo-electrocatalytic properties of g-C_3N_4. Int J Hydrogen Energy 53:925–934. https://doi.org/10.1016/j.ijhydene.2023.11.316

[48] Li Z, Ao J, Wang Z, Huang Z, Xu Z, Wu X, Cheng Z, Lv K (2024) Boosting the photocatalytic CO_2 reduction activity of g-C_3N_4 by acid modification. Sep Purif Technol 338:126577. https://doi.org/10.1016/j.seppur.2024.126577

[49] Arumugam M, Tahir M, Praserthdam P (2022) Effect of nonmetals (B, O, P, and S) doped with porous g-C_3N_4 for improved electron transfer towards photocatalytic CO_2 reduction with water into CH_4. Chemosphere 286:131765. https://doi.org/10.1016/j.chemosphere.2021.131765

[50] Jia Y, Tong X, Zhang J, Zhang R, Yang Y, Zhang L, Ji X (2023) A facile synthesis of coral tubular g-C_3N_4 for photocatalytic degradation RhB and CO_2 reduction. J Alloys Compd 965:171432. https://doi.org/10.1016/j.jallcom.2023.171432

[51] Hussien MK, Sabbah A, Qorbani M, Putikam R, Kholimatussadiah S, Tzou DM, Elsayed MH, Lu Y, Wang Y, Lee X, Lin T, Thang NQ, Wu H, Haw S, Wu KC-W, Lin M, Chen K, Chen L (2024) Constructing B—N—P Bonds in Ultrathin Holey g-C3N4 for Regulating the Local Chemical Environment in Photocatalytic CO_2 Reduction to CO. Small. https://doi.org/10.1002/smll.202400724

[52] Tarek M, Atta M, Shukor MZ, Abdullah H, Khan MR (2023) Highly effective B@g-C_3N_4/polyaniline nanoblend for photoelectrocatalytic reduction of CO_2 to methanol. Chem Eng Technol 46:2661–2669. https://doi.org/10.1002/ceat.202300035

[53] Rehman ZU, Bilal M, Rehman SU, Butt FK, Asghar Z, Zhang Y, Xu X, Hou J, Wang X (2025) Boron doped g-C_3N_4 porous nanosheets to increase electron-hole pair generation for excellent photocatalytic H_2 production and CO_2 reduction. Sep Purif Technol 354:129535. https://doi.org/10.1016/j.seppur.2024.129535

[54] Bafaqeer A, Aishah Saidina Amin N, Chennampilly Ummer A, Ahmed S, Al-Qathmi AT, Usman J, Kulal N, Tanimu G (2024) Well-designed glucose precursor carbon/g-C_3N_4 nanocomposite for enhanced visible light photocatalytic CO_2 reduction activity. J Photochem Photobiol A-Chem 447:115272. https://doi.org/10.1016/j.jphotochem.2023.115272

[55] Jothivenkatachalam K, Prabhu S, Nithya A, Jeganathan K (2014) Facile synthesis of WO_3 with reduced particle size on zeolite and enhanced photocatalytic activity. RSC Adv 4:21221–21229. https://doi.org/10.1039/C4RA01376J

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