

Photocatalytic fuel cell study: Wastewater treatment and electricity generation by using GCN and GCN/ZnO photoanode under solar light irradiation

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ABSTRACT

Graphitic carbon nitride (GCN) is an eco-friendly photosensitizer and a sustainable alternative to traditional metal oxide semiconductors in wastewater applications. This present investigation synthesized a hybrid composite of graphitic carbon nitride and zinc oxide (GCN/ZnO) using a simple calcination process, which was then mounted onto a carbon plate to serve as a photoanode in a photocatalytic fuel cell (PCF) to treat synthetic wastewater containing Reactive Red 120 (RR 120) dye while generating electricity using natural sunlight for a total of 6 hours of light exposure. The GCN/ZnO photoanode was evaluated and compared purely to the GCN-filled carbon plate photoanode. The GCN/ZnO photoanode produced 1.70 times more electricity, 1.05 times increase in reaction kinetics and the optimal color removal efficiency (61.96 %) as GCN-filled only carbon plates. In conclusion, the addition of ZnO into the GCN as a photoanode was beneficial towards photocatalytic and electrochemical activity in PFC.

1. INTRODUCTION

The increasing worldwide demand for sustainable energy solutions has intensified research into clean and renewable technologies. Among these clean energy technologies, photocatalytic fuel cells (PFCs) have emerged as promising systems that combine energy generation and environmental remediation by converting solar energy to electricity and degrading organic pollutants. As PFCs degrade organic pollutants while generating electricity, the performance of the photoanode is the most important consideration for the overall efficiency of PFCs as its performance designs the photoelectrochemical oxidation reactions during light irradiation.

Graphitic carbon nitride (GCN) has generated considerable excitement as a metal-free photocatalyst due to favorable bandgap (~2.7 eV), good thermal and chemical stability, and visible-light activity [1]. However, the real application is not realized due to its fast electron-hole recombination and limited light absorption [2]. To address these limitations, research found that modifying its structure, for example, doping, defect engineering and heterojunction etc. could enhance charge separation and increase the overall photoresponse [3]. One of the most common materials made into heterojunctions with GCN is zinc oxide (ZnO). ZnO is a wide bandgap (3.37 eV) semiconductor exhibiting excellent electron mobility that strongly absorbs in the UV region [4]. Studies found that the restriction of ZnO to visible light absorption capability can be resolved by modifying it through doping or

heterojunctions [5]. When it is synthesized together with GCN, ZnO serves to enhance the charge transfer of electrons to GCN, creating new paths for electrons to be excited to and from its conduction band and promoting the activation of new wavelengths of light.

In this research, a composite photoanode based on GCN/ZnO was fabricated and characterized for application in PFCs. The synergy between GCN and ZnO is expected to enhance photoelectrochemical performance by improving charge separation and light-utilization. The photoanode was fabricated and subsequently tested under simulated solar irradiation while the photocatalytic behavior and electrochemical behavior were studied systematically. This research will help in the development of efficient and low-cost photoanode materials for sustainable energy conversion with photocatalytic fuel cell systems.

2. EXPERIMENTAL PROCEDURE

2.1 Preparation of GCN-Loaded Carbon Plate (GCN/C) Photoanode

GCN and GCN/ZnO were synthesized through calcination methods. 20 g of urea was calcinated at 520°C with 3°C/min for 3 h. On the other hand, 2 g of zinc acetate dihydrate was mixed with 20 g of urea to synthesise GCN/ZnO by using the same heating rate, calcination temperature and duration of the method to synthesise

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GCN. A carbon plate as the substrate for the photoanode was prepared in the dimensions of $3.0 \times 3.0 \times 1.0$ cm. The synthesized GCN and GCN/ZnO suspension were then loaded on the carbon plate through immobilization method, then dried in the oven at 60°C for 2 hours and transferred to the muffle furnace at 80°C for 10 minutes for heat treatment.

2.2 PFC Setup and Operation

GCN/C and GCN/ZnO were applied as photoanodes while platinum-loaded carbon paper (Pt/C) was employed as the cathode in a 600 mL beaker with 250 mL 0.1 M Na_2SO_4 , 10 mg/L of RR120 to set up a PFC. The two electrodes were linked through an external circuit with a resistivity of 1 k Ω at 1 cm. The PFC system was provided with a flow rate of 0.4 L/min under sunlight irradiation for 6 hours of reaction time. The water sample was collected every hour, and the power density curve was recorded during the experiment.

3. RESULTS AND DISCUSSION

The RR120 colour removal efficiency as in Figure 2, for GCN/C photoanode shows 62.0 % of degradation efficiency, while the GCN/ZnO photoanode shows 61.96 % of degradation efficiency. Although the colour removal efficiency of GCN/ZnO/C photoanode was weaker than GCN/C photoanodes, the current density (J_{sc}) of GCN/ZnO/C photoanode is 53.27 mA/m^2 while GCN/C photoanode is 39.81 mA/m^2 as depicted in Figure 3. This can have an impact on electricity generation, which provides more electrical energy while undergoing a degradation process. It happened because the hybridization of ZnO into pristine GCN had improved charge mobility by reducing the electron-hole pair recombination, leading to higher current density.

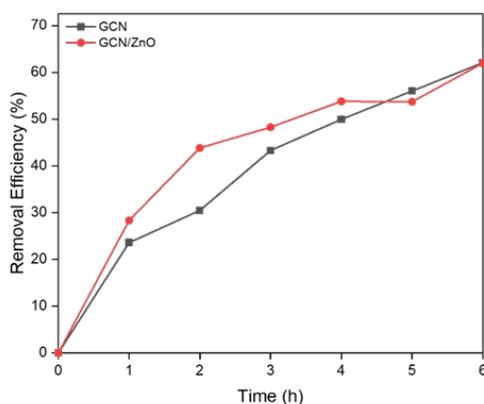


Figure 1. RR120 colour removal efficiency of GCN/C and GCN/ZnO/C photoanodes in PFC for 6 hours under solar light irradiation.

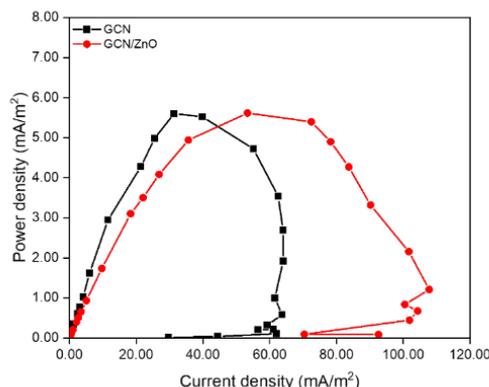


Figure 2. Power density curve of GCN/C and GCN/ZnO/C photoanodes in PFC under solar light irradiation.

4. CONCLUSION

In conclusion, GCN and GCN/ZnO photoanodes were successfully fabricated. The heterojunction of GCN and ZnO exhibits higher current density in the power density curve when its design promotes efficient charge separation, rapid electron transport, and broad light absorption. This study provided important insights for the synthesis and modification of GCN/ZnO composite for application as the photoanode in PFC to degrade azo dye and generate electricity synchronously. The future work can focus on using GCN/ZnO photoanodes to treat different kinds of wastewater or even real wastewater.

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REFERENCE

- [1] Ahmed, M. A., Mahmoud, S. A., & Mohamed, A. A. (2024). Unveiling the photocatalytic potential of graphitic carbon nitride (g-C₃N₄): a state-of-the-art review. *RSC Advances*, *14*(35), 25629–25662. <https://doi.org/10.1039/D4RA04234D>.
- [2] Baig, A., Siddique, M., & Panchal, S. (2025). A Review of Visible-Light-Active Zinc Oxide Photocatalysts for Environmental Application. *Catalysts* *2025*, Vol. 15, Page 100, *15*(2), 100. <https://doi.org/10.3390/CATAL15020100>.
- [3] Gao, J., Wang, S., Cai, H., Chen, S., Zheng, L., Li, Y., & He, G. (2025). Portable photocatalytic fuel cell with anatase/rutile TiO₂ heterophase junction for solar energy harvesting and pollutant degradation. *International Journal of Hydrogen Energy*, *97*, 259–269. <https://doi.org/10.1016/J.IJHYDENE.2024.11.316>.

- [4] Lopez, E. C. R. (2025). Transition metal dopants modulate the band gap and electronic structure of corrugated graphitic carbon nitride. *Next Materials*, 8, 100550. <https://doi.org/10.1016/J.NXMATE.2025.100550>.
- [5] Pattanayak, D. S., Dharm Pal, ., Mishra, J., & Chandrakant Thakur, . (2017). Noble metal-free doped graphitic carbon nitride (g-C₃N₄) for efficient photodegradation of antibiotics: progress, limitations, and future directions. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-022-20170-9>.
- [6] Pratomo, U., Fransisca, N., Adzani, M. D., Irkham, I., Sulaeman, A. P., Eddy, D. R., Mulyana, J. Y., & Primadona, I. (2025). Doping of rare earth element: The effects in elevated physical and optical properties of ZnO. *Talanta Open*, 11, 100411. <https://doi.org/10.1016/J.TALO.2025.100411>.