

Impact of illumination configuration on the performance of a dual-photoelectrode photocatalytic fuel cell

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ABSTRACT

Photocatalytic fuel cell (PFC) is an emerging sustainable technology for simultaneous wastewater remediation and energy recovery. This study investigates the effect of illumination configuration on dual-photoelectrode PFC performance using a batch-scale photocatalytic fuel cell with a working volume of 300 mL. The system utilizes a ZnO-loaded carbon plate as a photoanode and a graphitic carbon nitride (g-C₃N₄)-loaded carbon plate as a photocathode, since ZnO is a well-established photocatalyst and g-C₃N₄ is a sustainable and metal-free electrocatalyst. Using 10 ppm hydroquinone as a model organic pollutant under UVA irradiation, two illumination configurations were evaluated: single-sided and double-sided. The results revealed that the double-sided illumination (0.4103 mW m⁻²) yielded a minor 4.19% increase in maximum power density compared to single-sided illumination (0.3938 mW m⁻²), which was determined to be statistically non-significant ($p = 0.917$). These low power densities reflect that the PFC configuration targets organic pollutant degradation as its primary focus, with electricity generation serving merely as a secondary side product. The double-sided illumination demonstrated enhanced photocatalytic activity, with a removal efficiency of 66.35% and a pseudo-first-order rate constant of 0.1913 h⁻¹, surpassing the single-sided illumination (52.19% and 0.1257 h⁻¹). Simultaneously, for both systems, a progressive change was observed at 222 nm, indicating the accumulation of intermediate oxidation products during the degradation process. These results provided fundamental insights into how geometric illumination configuration affects the degradation efficiency and electricity generation in dual-photoelectrode architectures.

Keywords: illumination configurations, photocatalytic fuel cell, photocathode, electricity generation, degradation

1. INTRODUCTION

The discharge of organic pollutants into water bodies has become a serious environmental problem due to their toxicity, persistence, and resistance to conventional treatment processes [1]. Many wastewater treatment technologies require high energy consumption and complex operational conditions, which limit their sustainability. Therefore, the development of environmentally friendly technologies that are capable of concurrently degrading organic pollutants and recovering energy has become an important research topic.

Photocatalytic fuel cells (PFCs) have emerged as a promising technology that integrates photocatalysis and electrochemical energy conversion for concurrent wastewater treatment and energy recovery [2, 3]. In a typical PFC system, semiconductor photocatalysts are activated by light irradiation to generate electron-hole pairs. The photogenerated holes participate in the oxidation of organic pollutants. During the degradation process, for aromatic pollutants, partial degradation often yields temporary, toxic intermediate structures before achieving complete mineralization. While the excited electrons are transferred from the anode through an

external circuit to the cathode to produce electrical energy. This dual-function process enables the utilization of solar energy while removing contaminants from wastewater.

Among various photocatalysts, graphitic carbon nitride (g-C₃N₄) has gained significant attention because of its metal-free nature, chemical stability, and suitable band gap for light-driven photocatalysis [4]. In addition to the photocatalyst properties, the electrode configuration within the PFC reactor can significantly influence system performance. The orientation of electrodes relative to the light source may affect photon absorption, charge-carrier generation, and electron-transfer efficiency, which ultimately determine both electricity generation and pollutant removal efficiency [5]. Optimisation of these factors ensures uniform photon absorption across the active film surface and minimizes bulk recombination losses, thereby improving PFC performance [6].

Previous literature has predominantly focused on altering chemical operating parameters or catalyst materials to enhance PFC or dual-photoelectrode PFC outputs [6-10]. From a fundamental perspective, the illumination configuration is closely linked to the local photon distribution and light utilization efficiency inside the cell [5,

11]. However, specific studies systematically investigating the impact of illumination configuration in PFC systems remain very limited [12]. Consequently, the interaction between dual-photoelectrode illumination configurations and overall fuel cell performance deserves further investigation.

Therefore, this study presents a novel evaluation framework by investigating single- versus double-sided illumination configurations to explore the impact of electrode configurations on the performance of a photocatalytic fuel cell system using a g-C₃N₄-loaded carbon plate (g-C₃N₄/C) as the photocathode. In this study, hydroquinone was used as an organic contaminant, and the PFC performance was evaluated in terms of electricity generation and removal efficiency under UVA irradiation. To establish clear benchmarking parameters, this baseline study is limited to a single target pollutant, a fixed concentration of 10 ppm, a static electrode spacing, and a uniform catalyst loading. UVA light was selected to provide a stable, repeatable baseline light source emission capable of activating the semiconductor electrodes. The findings provide fundamental insights into how geometric illumination configuration affects degradation efficiency and electricity generation in dual-photoelectrode PFC systems, which has not been reported elsewhere.

2. MATERIALS AND METHODS

2.1. Chemicals

Hydroquinone (C₆H₆O₂, analytical grade, ≥ 99% purity, Acros Organics, Thermo Fisher Scientific, Geel, Belgium) was used as the model organic pollutant in this study. Melamine (C₃H₆N₆, analytical grade, ≥ 99% purity, Sigma-Aldrich, St. Louis, MO, USA) was employed as a precursor for the g-C₃N₄ as the photocathode material, while zinc oxide (ZnO, PRS grade, ≥ 99%, HmbG Chemicals, Germany) was used as the photocatalyst at the photoanode. Carbon plates were used as the supporting substrates for both electrodes. An ethanol, C₂H₅OH (95% purity, HmbG Chemicals, Germany), was used for cleaning purposes in this research. All analytical-grade reagents required no further purification. Distilled water and ethylene glycol (HOCH₂CH₂OH, analytical grade, ≥ 99.5% purity, Merck, Germany) were used to prepare the solutions.

2.2. Graphitic carbon nitride synthesis

The g-C₃N₄ was produced by calcining melamine at 580 °C for 4 h, utilizing a heating ramp rate of 10 °C/min. Then, the produced g-C₃N₄ was allowed to cool to ambient temperature and ground into a fine powder.

2.3. Preparation of electrodes

Carbon plates were prepared into 5 cm x 3 cm dimensions and were pre-cleaned before being used as substrates for electrodes. To prepare the anode, 2.0 g of ZnO was magnetically and ultrasonically dispersed in distilled water. After that, the ZnO suspension was uniformly

distributed on the carbon plate and underwent thermal treatment (200 °C) for 2 h. To prepare the cathode, 0.3 g of g-C₃N₄ was magnetically and ultrasonically dispersed into a mixed solution of distilled water and ethylene glycol. After that, the prepared suspension was applied uniformly on the carbon plate and underwent thermal treatment at 170 °C for 15 min.

2.4. PFC construction

The photocatalytic fuel cell (PFC) consisted of a ZnO-coated carbon plate photoanode and a g-C₃N₄-coated carbon plate photocathode. Schematic illustrations of the illumination configurations are presented in Figure 1 and Figure 2. Figure 1 shows the double-sided illumination configuration, and Figure 2 represents the single-sided illumination configuration. For the single-sided illumination configuration, the coated surfaces of both electrodes were exposed to a single UVA light source (36 W/78, 315–400 nm, 2G11). For the double-sided illumination configuration, two UVA light sources were positioned on opposite sides of the reactor while maintaining the coated surfaces of both electrodes facing the incident light. The electrodes were placed at an inter-electrode distance of 1 cm in the reactor containing hydroquinone solution (300 mL, 10 mg L⁻¹). Air was continuously supplied at 0.2 L min⁻¹ throughout the experiment. The electrodes and the UVA lamp distance were maintained at 7 cm. A 1kΩ external resistance was connected between the anode and cathode throughout the experiment to facilitate electron transfer and monitor electricity generation. All the experiments were performed in triplicate (n = 3).

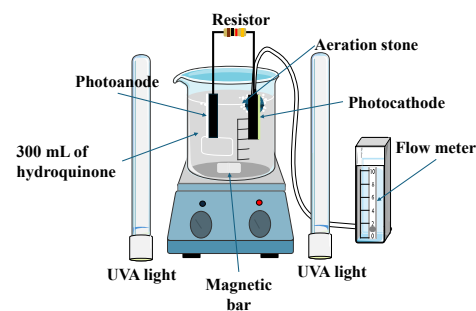


Figure 1. Schematic diagram of double-sided illumination configuration for the PFC system.

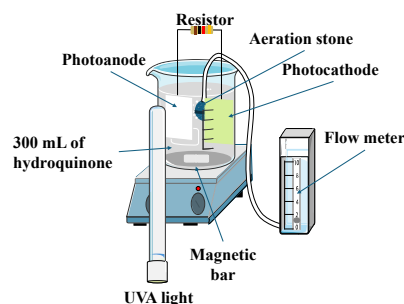


Figure 2. Schematic diagram of a single-sided illumination configuration for the PFC system.

2.5. Materials Characterization

The crystal structure of the g-C₃N₄ was analyzed using X-ray diffraction (XRD, D2 Phaser) over a 2θ range of 5–80° utilizing Cu K_α radiation (λ = 1.5406 Å). The morphology of the samples was investigated with scanning electron microscopy (SEM, JEOL JSM 6460 LA). A thin layer of platinum was applied to the sample before imaging with a JEOL auto fine coater machine (Model: JFC-1600) to enhance the quality of the SEM imaging.

2.6. Evaluation of performance in illumination configurations

The electricity generation performance of single-sided and double-sided illumination configurations was analyzed by polarization measurement assisted with a ZX21, DongMao, Shanghai, China, adjustable resistance box from 10 to 1 MΩ, 1-minute stabilization dwell time was allowed, and the voltages were measured using a Sanwa multimeter (CD800a, Japan). The results were subsequently converted into current density, *J*, by Eq. 1 and power density, *P*, by Eq. 2:

$$\text{Current density, } J = V / (R_{\text{ext}} \times A) \quad (1)$$

where *V* is the corresponding voltage, *R_{ext}* is the external resistance, and *A* is the electrode area.

$$\text{Power density, } P = (V \times I) / A \quad (2)$$

where *V* is the corresponding voltage, *I* is the current, and *A* is the electrode area.

The degradation performance of single-sided and double-sided illumination configurations was examined by a UV-Vis spectrophotometer from Mesulab, China (Model: ME-UV1200PC) at a wavelength of maximum absorbance of 289 nm. Standard calibration plots of target peak absorbance against precise linear concentrations (*R*² > 0.99) were utilized for all UV-Vis concentration calculations. Then, the results were turned into the colour removal efficiency by Eq. 3:

$$\text{Colour removal efficiency} = (C_0 - C) / C_0 \times 100\% \quad (3)$$

where *C* is the concentration at the specified reaction time in unit hours and *C*₀ is the initial concentration.

The degradation kinetics of each single-sided and double-sided illumination configuration were evaluated by a pseudo-first-order kinetic model. The linear plot was plotted, and the slope correlates to the rate constant (*k*), which was used to compare the two systems, as in Eq. 4:

$$\ln C_0 / C = kt \quad (4)$$

where *C*₀ and *C* represent the initial concentration and the concentration at a specified time, *t*, and *k* is the pseudo-first-order apparent rate constant, respectively.

A control experiment was conducted to evaluate the effect of the illumination configuration on the direct photolysis of hydroquinone. The hydroquinone solution was exposed to either single-sided or double-sided UVA illumination for 6 h. Samples were collected at predetermined time intervals, and the remaining hydroquinone concentration was determined using UV-Vis spectrophotometry from Mesulab, China (Model: ME-UV1200PC). This control experiment was conducted to distinguish the contribution of the illumination configuration and direct photolysis from the photocatalytic degradation observed in the photocatalytic fuel cell system.

A reusability test for single-sided and double-sided illumination configurations was conducted over three consecutive cycles. The electrodes were rinsed with distilled water and allowed to dry after completing each cycle.

3. RESULTS AND DISCUSSION

3.1. Phase and morphology analysis

The structural phase of g-C₃N₄ was examined by XRD, and the diffraction pattern is shown in Figure 3. As shown in Figure 3, there are two characteristic diffraction peaks observed at 2θ approximately 13.1° and 27.4°, corresponding to the (100) and (002) crystallographic planes of g-C₃N₄, respectively, which can be indexed to JCPDS card no. 87-1526 g-C₃N₄ data. The peak at 13.1° is associated with the in-plane structural packing of tri-s-triazine units. In comparison, the strong diffraction peak at 27.4° is attributed to interlayer stacking of the conjugated aromatic layers within the graphitic structure [13-15].

The presence of these characteristic peaks validates the successful formation of graphitic carbon nitride without altering its fundamental crystal framework during thermal synthesis. Furthermore, the relatively sharp and intense (002) diffraction peak indicates a well-developed layered structure and good crystallinity of the synthesized g-C₃N₄. Similar diffraction features have been reported for synthesized graphitic carbon nitride [16-18].

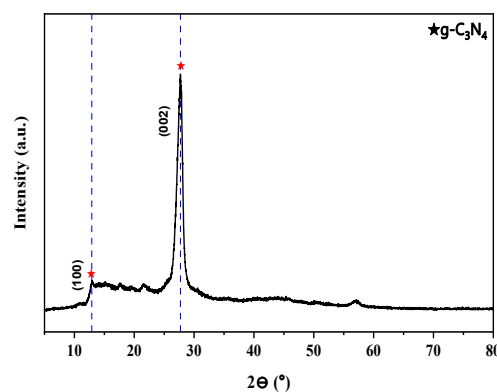


Figure 3. XRD pattern for g-C₃N₄.

The synthesized $\text{g-C}_3\text{N}_4$ (powder) was examined by SEM, and the surface morphology is shown in Figure 4. The SEM image revealed an irregular layered structure consisting of stacked and agglomerated sheets, which is characteristic of $\text{g-C}_3\text{N}_4$ [19]. The layered morphology is due to the graphitic arrangement of the conjugated aromatic units within the $\text{g-C}_3\text{N}_4$ framework. To complement the morphological observation, Brunauer–Emmett–Teller (BET) nitrogen adsorption–desorption analysis was performed to evaluate the textural properties of the material. The synthesized $\text{g-C}_3\text{N}_4$ exhibited a specific surface area of $74.48 \text{ m}^2 \text{ g}^{-1}$. This supported that such a structure can offer a relatively large surface area, as previously reported [20]. Besides, it facilitated the interaction between the catalyst and reactant molecules during the photocatalytic process, providing the electrons needed for high charge mobility across the planar sheets [21]. The observed morphology is consistent with the previous structure reported for $\text{g-C}_3\text{N}_4$, indicating that the synthesized material retained its layered graphitic framework after preparation [22, 23].

To assess the structural profile of the complete assembled photoelectrodes, a macro-scale surface photograph of the final coated substrate was presented as shown in Figure 5. It reveals a uniform, continuous catalyst layer across the entire face of the carbon plate substrate. This uniform surface coverage promotes consistent light exposure across the film and supports stable contact between the electrolyte and the electrode surface.

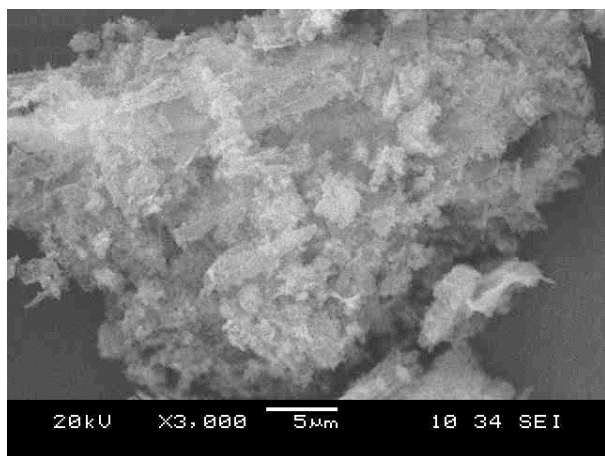


Figure 4. SEM image of synthesized $\text{g-C}_3\text{N}_4$ at 3k magnification.

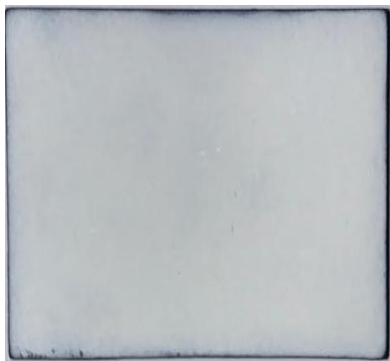


Figure 5. Macro-scale surface photograph of the assembled $\text{g-C}_3\text{N}_4$ -loaded carbon plate photocathode.

3.2. Effect of Illumination Configuration on Hydroquinone Photolysis

To investigate the effect of illumination intensity, a photolysis study was conducted using 10 mg L^{-1} hydroquinone under single-sided and double-sided illumination configurations. As shown in Figure 6, a negligible degradation (below 3%) of hydroquinone was observed for both illumination configurations. The removal efficiency between the two illumination configurations showed a trivial difference. The findings indicate that the UVA light alone did not significantly degrade hydroquinone, nor did an additional UVA light source enhance its direct photolysis. Therefore, the degradation performance observed in the PFC system under double-sided illumination cannot be solely attributed to increased light intensity.

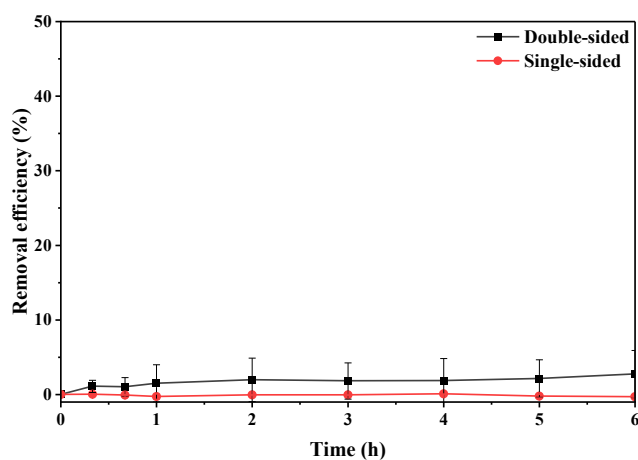


Figure 6. Photolysis of hydroquinone under single-sided and double-sided illumination configurations.

3.3. Effect of different illumination configurations on hydroquinone degradation

Figure 7 shows the hydroquinone removal efficiency under single-sided and double-sided illumination configurations. The removal efficiency increased progressively with irradiation time for both configurations, indicating continuous degradation of hydroquinone throughout the reaction period. However, the double-sided illumination configuration consistently exhibited higher removal efficiency than the single-sided illumination configuration.

After 6 h of operation, the double-sided illumination configuration achieved approximately 66.35% of hydroquinone removal, whereas the single-sided illumination configuration attained only about 52.19% of removal. This indicated that the double-sided illumination configuration PFC system exhibited superior degradation performance compared to the single-sided illumination configuration PFC system.

In the PFC system, the degradation of pollutants is mainly driven by photocatalytic reactions occurring at the illuminated electrodes [24]. Upon UVA irradiation, electrons in the valence band (VB) of ZnO (photoanode) are promoted to the conduction band (CB), leaving behind

positive holes (h^+) in the VB (Eq. 5). The photogenerated holes can directly oxidize hydroquinone molecules that are adsorbed on the electrode surface (Eq. 6):

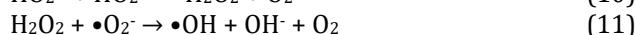


Simultaneously, the electrons are transmitted through the outside circuit to the g-C₃N₄ photocathode due to the bias of potential, with a higher potential in ZnO and a lower potential energy in g-C₃N₄, and participate in reduction reactions, thereby contributing to electricity generation [2, 25].

Then, the electrons in the VB of g-C₃N₄ are excited to the CB, leaving behind positive h^+ in the VB (Eq. 7). The photogenerated electrons react with oxygen molecules to become superoxide radicals ($\bullet\text{O}_2^-$) as shown in Eq. 8:



The generated superoxide radicals may subsequently react to become hydrogen peroxide (H_2O_2) and hydroxyl radicals ($\bullet\text{OH}$), which assist in the degradation of hydroquinone (Eqs. 9–11) [26]:



In addition, photogenerated h^+ may react with water molecules or hydroxide ions to $\bullet\text{OH}$ (Eq. 12):



The $\bullet\text{OH}$, $\bullet\text{O}_2^-$, and h^+ are reactive species that oxidize hydroquinone molecules and progressively convert them into intermediate or degraded products.

Since both the PFC systems' conditions are identical, just the photoelectrode illumination configuration is different, which means the degradation process should be the same, and the results are fully dependent on the photoelectrode illumination configuration in this study. This indicated that the superior performance of the double-sided illumination configuration may be attributed to the spatial separation of the reactive species produced by both photoelectrodes on the surface of the electrode once the UVA light irradiation occurs. In this setup, the photoelectrodes are positioned double-sided to face their respective opposing light sources. Upon UVA irradiation, the reactive oxidizing and reducing species are generated on opposite outer surfaces of the electrodes. This structural segregation minimizes lateral crossover, preventing self-neutralization and providing a significantly higher probability for the produced radicals to interact with and degrade the target hydroquinone molecules in the bulk solution.

In contrast, the single-sided configuration forces the active coatings of both electrodes to face the same direction. The lower performance observed under this configuration may be associated with localized charge accumulation and increased charge carrier recombination. Under irradiation, the photogenerated charge carriers, as well as the reactive oxygen species generated at the electrode surfaces, are concentrated within a relatively small reaction zone. Such localization may increase the probability of charge recombination and undesired interactions between oxidizing and reducing species before they participate in hydroquinone degradation, thereby diminishing removal efficiency. Therefore, compared to the single-sided illumination configuration, more reactive species were utilized in the double-sided illumination configuration PFC system, leading to enhanced degradation of hydroquinone in the double-sided illumination configuration.

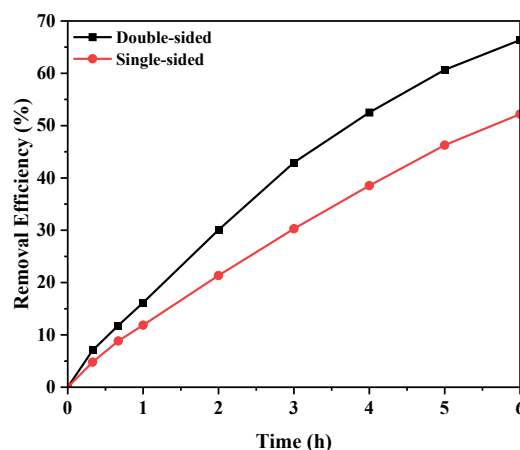


Figure 7. Removal efficiency of PFC systems for different electrode configurations.

Figures 8 and 9 show the UV-Vis wavelength scan analysis of hydroquinone for double-sided illumination configuration and single-sided illumination configuration in PFC, respectively, during PFC treatment. As shown in Figures 8 and 9, the depletion of absorbance peaks of hydroquinone under both single-sided and double-sided illumination configurations exhibited similar trends throughout the reaction period of 6 h. In both cases, the characteristic absorption band of hydroquinone at approximately 289 nm gradually decreased over time, indicating the progressive degradation of hydroquinone [27, 28]. Simultaneously, changes at 222 nm were observed progressively, suggesting the accumulation of intermediate oxidation products during degradation [29]. Besides, some spectral overlap may occur between aromatic intermediates (such as benzoquinone) and carboxylic acid formation (oxalic acid, formic acid) in the lower UV region; the characteristic peak at 289 nm remained well resolved and was utilized as the primary tracking wavelength [30]. This ensured that the calculated removal efficiencies accurately reflected the depletion of the parent

hydroquinone compound. The similar spectral profiles indicated that hydroquinone degradation followed the same reaction pathway under both illumination configurations. Therefore, the superior degradation performance observed under double-sided illumination is attributed to an enhanced degradation rate rather than a change in the degradation mechanism. This observation is consistent with the solution pH (Figure 10), where the pH remained stable with only a minor variation from 6.85 to approximately 6.2–6.3 across both configurations. This minor drop indicated the formation of slightly acidic intermediate species during hydroquinone degradation. The similar trends supported the UV-Vis spectra analysis that the illumination configuration did not alter the underlying reaction pathways.

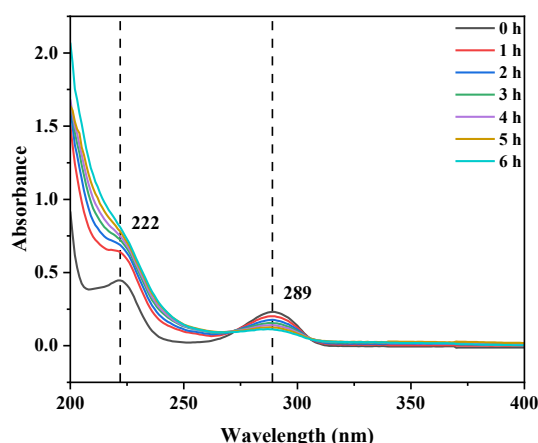


Figure 8. Wavelength scan of 10 mg L⁻¹ hydroquinone for double-sided illumination configuration over a period of 6 h.

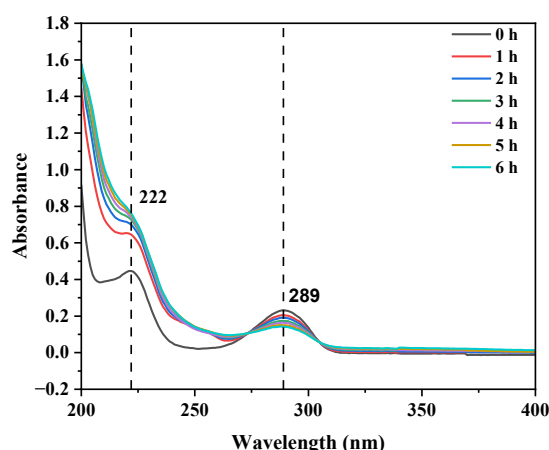


Figure 9. Wavelength scan of 10 mg L⁻¹ hydroquinone for single-sided illumination configuration over a period of 6 h.

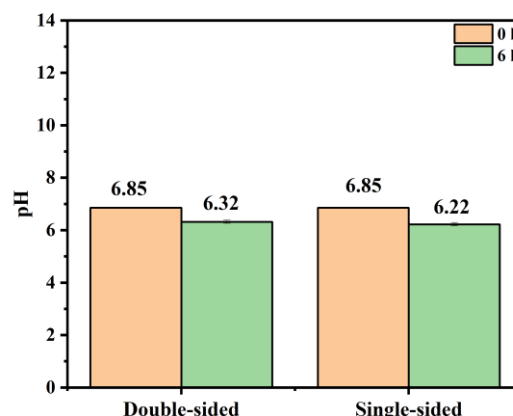


Figure 10. Hydroquinone solution pH before and after the 6-h reaction.

3.4. Kinetic study of different illumination configurations on hydroquinone degradation

The degradation kinetics of hydroquinone under different illumination configurations were evaluated using the pseudo-first-order kinetic model, as shown in Figure 8. Figure 11 represents the pseudo-first-order kinetics plot of PFC systems for different electrode configurations with hydroquinone at 10 mg L⁻¹. The apparent rate constants (k) were calculated from the slopes of the fitted lines. A higher k_1 value (0.1913 h⁻¹) was obtained for the system with the double-sided illumination configuration compared to the k_2 value (0.1257 h⁻¹) for the single-sided illumination configuration, indicating enhanced photocatalytic activity. Both k values possessed a good linear regression coefficient (R^2 of $k_1 = 0.9996$; R^2 of $k_2 = 0.9995$), indicating that the reaction has a good agreement with pseudo-first-order kinetics. The kinetic results are consistent with the hydroquinone removal efficiencies observed in Figure 7, where the double-sided illumination configuration achieved superior pollutant removal throughout the reaction period. The double-sided illumination configuration likely promoted more efficient generation and utilization of reactive oxygen species, thereby accelerating hydroquinone oxidation and improving the overall removal efficiency.

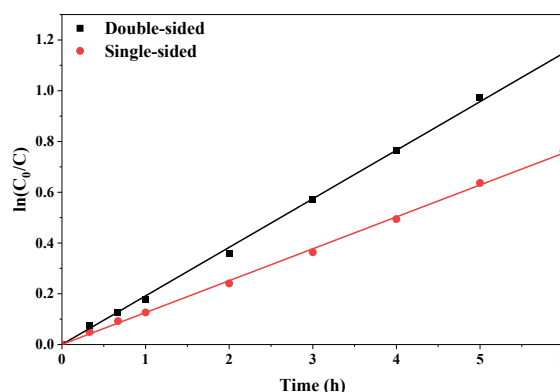


Figure 11. Pseudo-first-order kinetics plot of PFC systems for different illumination configurations.

3.5. Effect of different illumination configurations on electricity generation

Figure 12 and Figure 13 show the polarization curves and power density curves of PFC systems for different electrode configurations, respectively. As observed in Figures 12 and 13, the single-sided illumination configuration exhibited a higher open-circuit voltage (133.77 mV) than the double-sided illumination configuration (110.4 mV). The higher OCV indicates a larger potential difference between the electrodes under open-circuit conditions, suggesting that the single-sided configuration maintained a higher cell potential when no external current was drawn from the system [31].

However, despite the lower OCV, the double-sided illumination configuration achieved a slightly higher maximum power density (0.4103 mW m^{-2}) than the single-sided illumination configuration (0.3938 mW m^{-2}). This difference was not statistically significant, as confirmed by an unpaired two-sample t-test ($p=0.917$), indicating that the measured difference in power density was small relative to the variation among the experimental replicates. The difference between OCV and P_{max} could be explained by the fact that maximum power output was not determined solely by the open-circuit potential but also by the current generated and the voltage maintained under load. Electrode configuration and spacing have been reported to influence internal resistance, mass transport, and electrochemical performance in single-chamber fuel cell systems [32].

In the present system, the directly opposing electrode arrangement under double-sided illumination may have provided a different ionic transport environment compared with the side-by-side arrangement under single-sided illumination [33]. This difference may have influenced the electrical performance under load, allowing the double-sided configuration to produce a slightly higher measured P_{max} despite its lower OCV compared to the single-sided configuration. Conversely, although the single-sided configuration exhibited a higher OCV, its power output may have been limited by its current-generation and polarization characteristics. Overall, the results suggested that the illumination configuration influenced the balance between voltage and current generation, while the P_{max} values indicated that neither configuration provided a significant advantage in overall power generation under the conditions investigated. The relatively low power densities indicated that the energy recovery capability of the PFC remained limited under the conditions investigated. Therefore, the present study was primarily intended as a fundamental comparative assessment of how changes in physical illumination configuration affected the electrochemical performance of the PFC, rather than as an optimization of power generation.

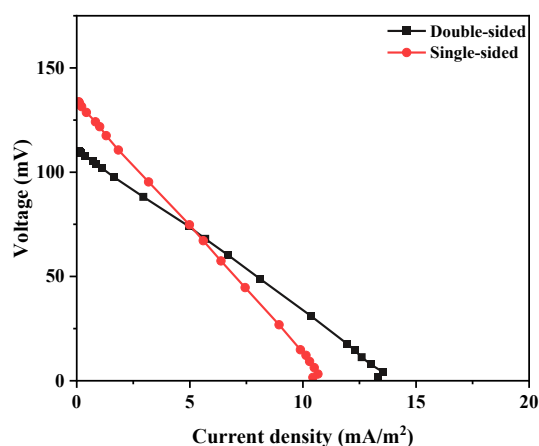


Figure 12. Polarization curves of PFC systems for different electrode configurations.

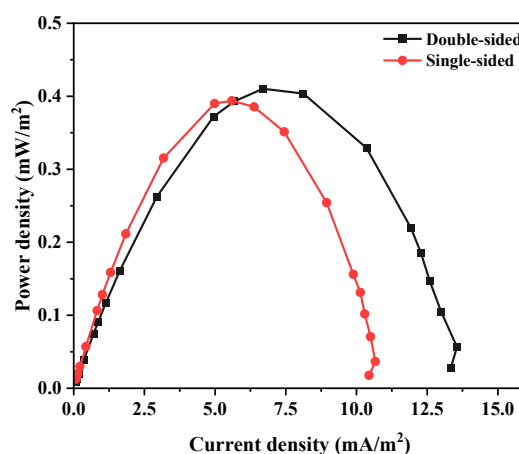


Figure 13. Power density curves of PFC systems for different electrode configurations.

3.6. Reusability test

To evaluate the stability of the prepared photoelectrodes, consecutive reusability trials were performed over three continuous cycles (total 1080 min) for both double-sided and single-sided (Figure 14) illumination configurations (Figure 15). As illustrated in Figure 14, the double-sided configuration exhibited a progressive decline in hydroquinone removal performance, with the final C/C_0 ratio rising from approximately 0.24 in the first cycle to 0.27 in the second and reaching 0.50 by the third cycle. Similarly, the single-sided configuration (Figure 15) showed an activity loss, where the final C/C_0 ratio shifted from 0.37 to 0.47 before experiencing a more pronounced drop to 0.61 in the final cycle. This gradual reduction in degradation efficiency points to a clear activity loss over cycles. This loss is maybe attributed to minor catalyst detachment, as well as the potential accumulation of

strongly adsorbed intermediate byproducts on the catalyst surface, which blocks the active surface sites over time.

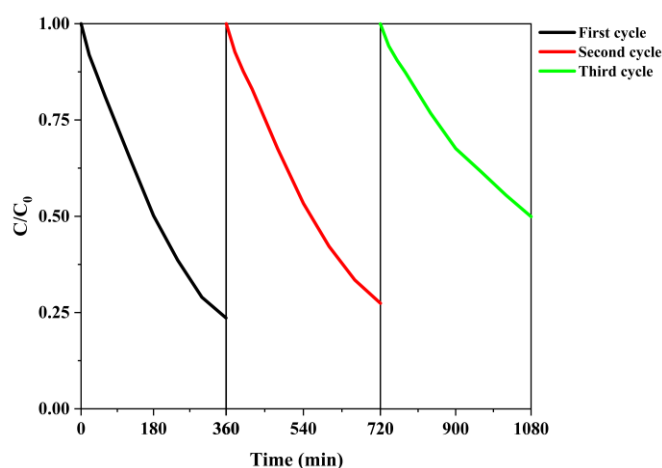


Figure 14. Recyclability test of double-sided illumination configurations PFC system.

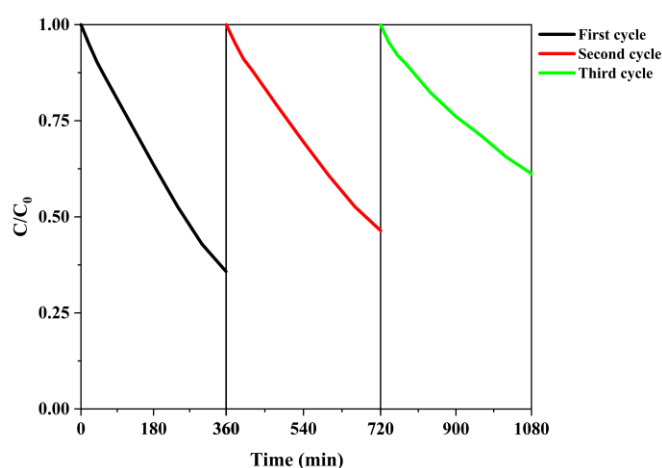


Figure 15. Recyclability test of single-sided illumination configurations PFC system.

4. CONCLUSION

In this study, the effect of illumination configuration on the performance of a g-C₃N₄-based photocathode photocatalytic fuel cell (PFC) for concurrent a single-target 10 ppm hydroquinone degradation and electricity production under a stable UVA light irradiance of 315–400 nm was investigated. Photolysis experiments showed negligible differences between the two illumination configurations, indicating that the enhanced performance was primarily attributed to improved photoelectrochemical activity rather than direct photolytic degradation. The results demonstrated that the single-sided illumination configuration yielded a higher open-circuit voltage (OCV) of 133.77 mV compared to the double-sided illumination configuration (110.4 mV). Conversely, the double-sided illumination configuration achieved a higher maximum power density (0.4103 mW m⁻²) and hydroquinone removal efficiency (66.35%) than the single-sided illumination configuration (0.3938 mW m⁻²; 52.19%). The UV-Vis spectral scan showed that the degradation of hydroquinone for double-sided and single-sided illuminations was identical. Kinetic analysis revealed

a faster degradation rate under double-sided illumination, following pseudo-first-order kinetics. The findings demonstrate that illumination configuration plays a critical role, providing fundamental insights into how geometric lighting factors influence the degradation and electrochemical response profiles of dual-photoelectrode PFC systems.

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