

Visible light-driven CoMoO₄/g-C₃N₄ photocatalyst for removal of antibiotic contaminant from wastewater

Kim Jitae^{a,b}, Minh Viet Nguyen^c, Pham Thi Huong^{d,*}

^a Institute of Research and Development, Duy Tan University, Da Nang, Vietnam

^b School of Engineering & Technology, Duy Tan University, Da Nang, Vietnam

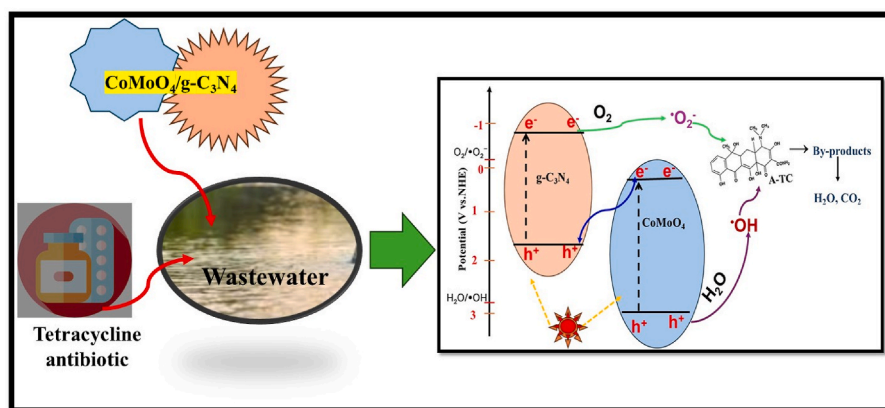
^c VNU Key Laboratory of Advanced Material for Green Growth, Faculty of Chemistry, VNU University of Science, 334 Nguyen Trai Street, Thanh Xuan, Hanoi, Vietnam

^d Department of Materials Science and Engineering, Gachon University, 1342 Seongnam-daero, Sujeong-gu, Seongnam, 13120, South Korea

HIGHLIGHTS

- CoMoO₄/g-C₃N₄ heterojunction photocatalyst was prepared.
- CoMoO₄/g-C₃N₄ showed greatly improved degradation efficiency of antibiotic pollutants.
- CoMoO₄/g-C₃N₄ effectively removed 80.2 % antibiotic pollutant from wastewater.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, CoMoO₄/g-C₃N₄ heterojunction photocatalyst was synthesized and utilized to enhance the photodegradation efficiency of the tetracycline antibiotic pollutant (A-TC) in wastewater. The results from UV-Vis and photoluminescence analysis indicate that the optical properties and the separation rate of photogenerated electrons/holes in the CoMoO₄/g-C₃N₄ heterojunction photocatalyst are significantly improved. Under the same conditions, CoMoO₄/g-C₃N₄ heterojunction photocatalyst effectively removed 91.3 % of A-TC from the solution, which is significantly higher than the removal efficiencies of g-C₃N₄ (68.7 %) and CoMoO₄ (57.9 %). Moreover, the photodegradation efficiency of A-TC in wastewater using CoMoO₄/g-C₃N₄ was 80.2 %, suggesting the potential of the synthesized heterojunction photocatalyst for practical water treatment. In addition, the proposed degradation mechanism of A-TC using the CoMoO₄/g-C₃N₄ heterojunction photocatalyst is founded on the Z-scheme and the role of free radicals.

* Corresponding author. Department of Materials Science and Engineering, Gachon University, 1342 Seongnam-daero, Sujeong-gu, Seongnam, 13120, South Korea.

E-mail addresses: kimjitae@duytan.edu.vn (K. Jitae), phambary@gachon.ac.kr (P. Thi Huong).

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1. Introduction

Currently, environmental pollution, particularly of water sources, poses a significant threat to ecosystems and human health worldwide [1–3]. In recent years, water pollution containing drugs and antibiotic compounds has contributed to the emergence of antibiotic-resistant bacteria [4–6]. The negative effects of antibiotic-resistant bacteria on human health have been investigated, with various serious issues such as prolonged infections, higher medical costs, and increased mortality rates. The growing prevalence of these bacteria brings a major challenge to healthcare systems around the world [7–15].

Tetracycline (A-TC) antibiotic is widely used to kill bacteria and treat infections in both humans and animals. As a result, large amounts of A-TC residues have been found in aquatic environments, leading to various impacts on human health and the ecosystem [12,14,16,17]. Therefore, finding a suitable method to remove antibiotic pollutants is urgent to prevent the generation of secondary pollutants and antibiotic-resistant bacteria [12,14,18]. Removal of antibiotic pollutants using the photocatalysis process is a popular and promising method due to its simplicity, high efficiency, and lack of reliance on complex equipment [2,3,7,15–17,19]. Photocatalysis utilizes light to activate catalysts that break down pollutants into harmless substances, offering a sustainable and environmentally friendly approach to water purification [15,17,20]. This technology shows great potential for addressing the complex challenges of water pollution, offering hope for the restoration and preservation of clean water sources for future generations. However, further research and development are needed to optimize photocatalytic processes and scale up their application to effectively combat the ongoing environmental degradation caused by pollution.

Molybdate photocatalytic materials are esteemed for their versatile applications across various fields, notably in environmental and energy-related sectors [19,21–27]. Among them, cobalt molybdate (CoMoO₄) distinguishes itself with remarkable properties and diverse uses. Specifically, cobalt molybdate exhibits an ideal band gap energy (2.5–3.0 eV), making it highly suitable for photocatalytic processes [25–28].

Graphitic carbon nitride (g-C₃N₄) is also known as a highly valuable material with a unique structure comprising carbon and nitrogen atoms arranged in a honeycomb lattice resembling graphene. This two-dimensional polymer exhibits intriguing properties, particularly its band gap energy, which falls within the visible light spectrum (up to 460 nm), enabling efficient solar energy utilization for photocatalytic reactions [1–3,29]. However, g-C₃N₄ exhibits some limitations in photocatalytic performance due to rapid electron-hole pair recombination, restricted surface area, and insufficient light absorption. To overcome these limitations, modification through heterostructure design or elemental doping can effectively boost photocatalytic efficiency [2,30]. Therefore, in the current work, CoMoO₄/g-C₃N₄ heterojunction photocatalyst was synthesized to enhance its photocatalytic degradation of A-TC in wastewater. The combination of g-C₃N₄ and CoMoO₄ is expected to effectively adjust the band gap energy, enhance visible light absorption, promote efficient charge carrier separation, and improve the removal efficiency of antibiotic residues.

2. Materials and methods

2.1. Synthesis and characterization of photocatalysts

The procedures for synthesizing and characterizing the photocatalysts (CoMoO₄, g-C₃N₄, and CoMoO₄/g-C₃N₄) are detailed in Text S1 (Supporting Material).

2.2. Photocatalytic experiments

A 30 W compact lamp was utilized to provide visible light, which was used for all degradation experiments in this study. Photocatalytic assessments were performed in a glass vessel containing 50 mL of A-TC solution (5–50 mg/L) and 0.03 g of catalyst material. The A-TC solution containing the photocatalyst was magnetically stirred in the dark at room temperature for 60 min to achieve adsorption-desorption equilibrium. Then, the degradation performance of A-TC was assessed under visible light using CoMoO₄, g-C₃N₄, and CoMoO₄/g-C₃N₄. During the photocatalytic degradation of A-TC, a small aliquot of the solution was withdrawn every 30 min and analyzed using a UV–visible spectrophotometer to determine the concentration of the remaining pollutant. The stability of the CoMoO₄/g-C₃N₄ photocatalyst was assessed by applying it in four consecutive reuse cycles. Total organic carbon analysis and radical quenching were employed to understand the mechanisms of A-TC degradation by the CoMoO₄/g-C₃N₄ photocatalyst.

The degradation efficiency of A-TC is calculated using the following equation (1):

$$H = \frac{C_0 - C_t}{C_0} \times 100\% \quad (1)$$

here, H (%) represents the degradation efficiency of A-TC. C_t (mg/L) and C₀ (mg/L) correspond to the concentration of A-TC at time t and the initial concentration, respectively.

3. Results and discussion

3.1. Characterization of CoMoO₄, g-C₃N₄ and CoMoO₄/g-C₃N₄

The surface morphology of the material was examined through scanning electron microscopy (SEM), with the results shown in Fig. 1. It can be observed that the graphitic carbon nitride synthesized in this work exhibits a structure composed of stacked flat layers with irregular shapes (Fig. 1a). Besides, the morphology of CoMoO₄/g-C₃N₄ exhibits a characteristic two-dimensional structure with stacked layers of graphitic carbon nitride, and small particles of CoMoO₄ are randomly distributed on the layers of g-C₃N₄ (Fig. 1b) [19,21,22,27,28,30].

The Energy Dispersive X-ray Spectroscopy (EDS) analysis, along with elemental mapping, demonstrates the presence of carbon (C), nitrogen (N), cobalt (Co), molybdenum (Mo), and oxygen (O) in the sample, confirming the successful incorporation and combination of CoMoO₄ with g-C₃N₄ (Fig. 2). In addition, the elemental mapping analysis further demonstrates the placement of CoMoO₄ on the surface of graphitic

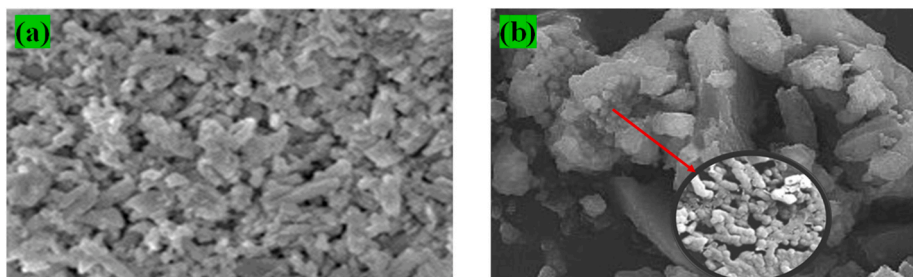


Fig. 1. Surface morphologies of (a) g-C₃N₄ and (b) CoMoO₄/g-C₃N₄.

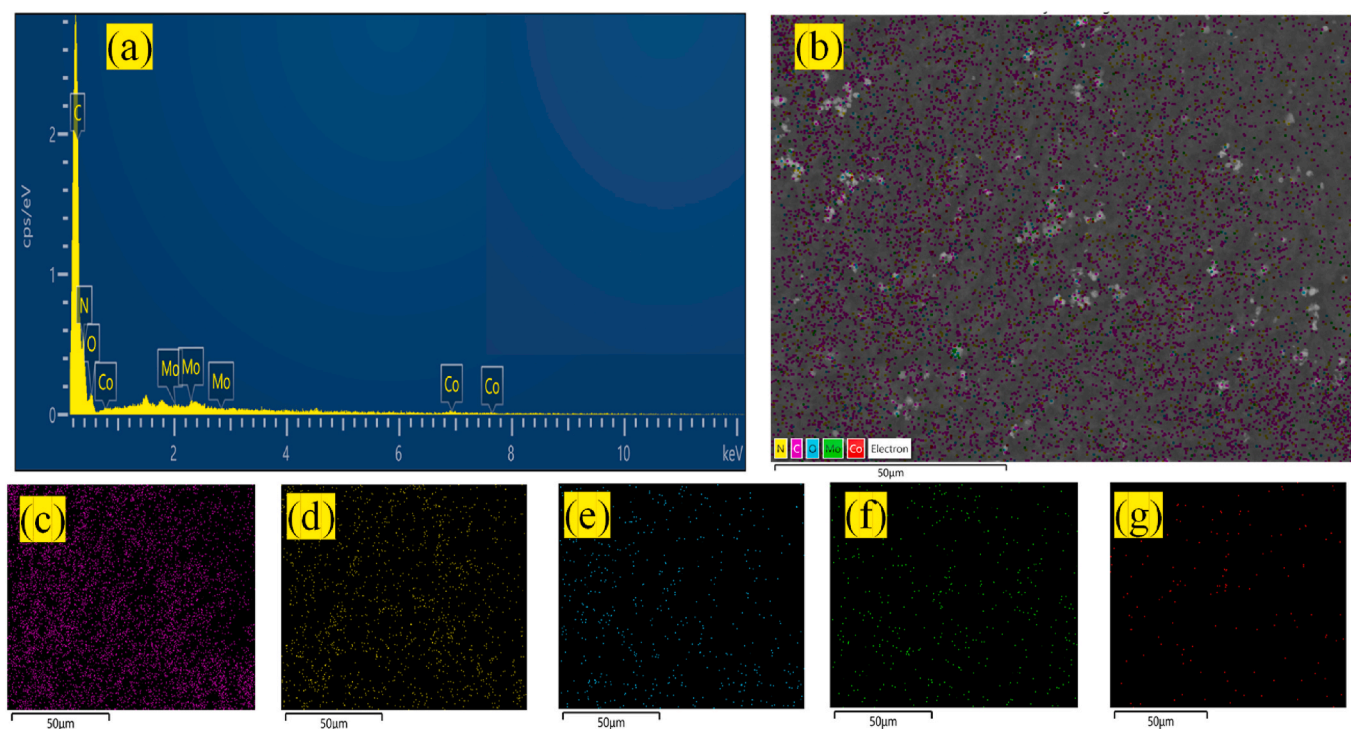


Fig. 2. EDS analysis of $\text{CoMoO}_4/\text{g-C}_3\text{N}_4$ (a) and elemental mapping images of $\text{CoMoO}_4/\text{g-C}_3\text{N}_4$ (b), carbon (c), nitrogen (d), oxygen (e), molybdenum (f), and cobalt (g).

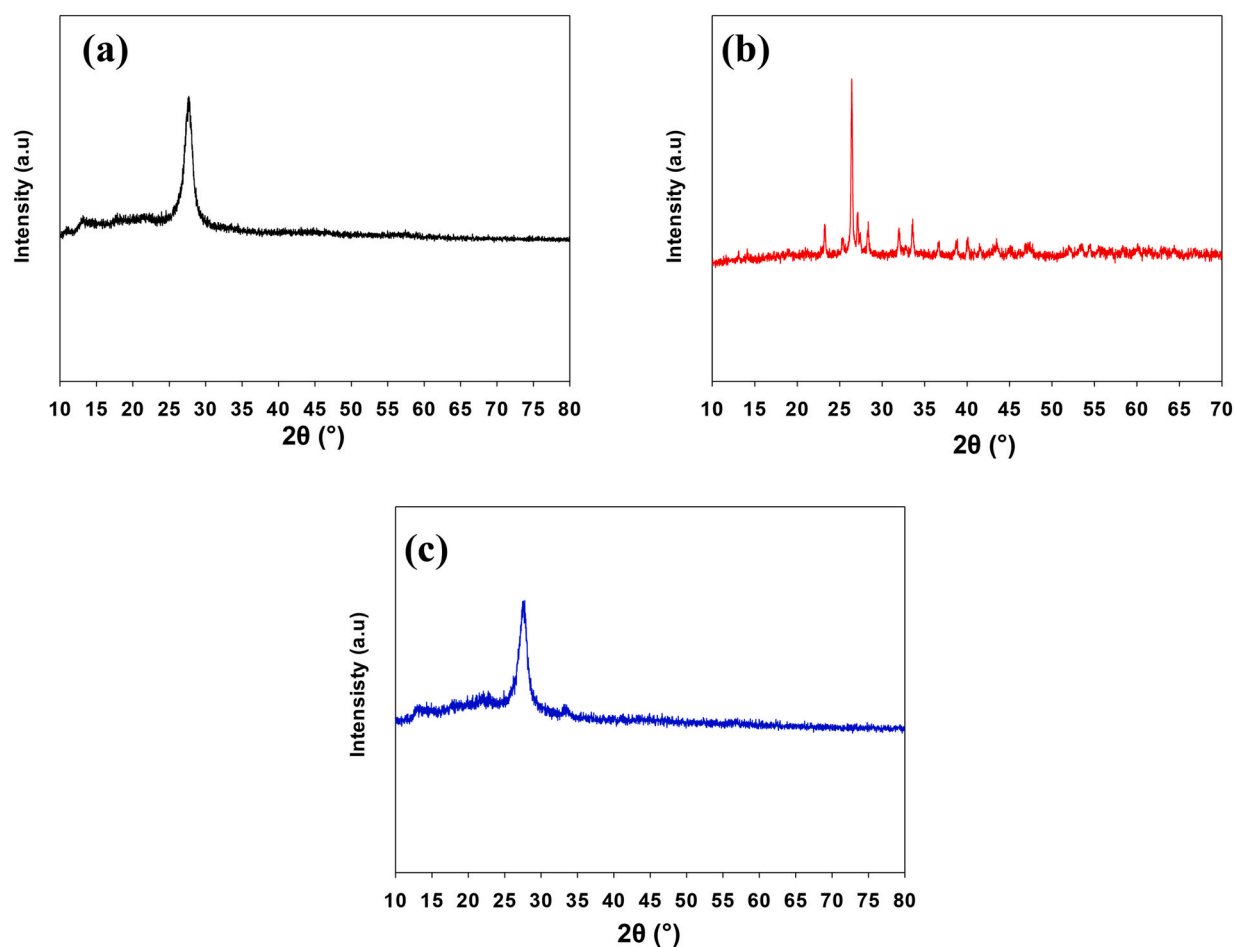


Fig. 3. XRD patterns of $\text{g-C}_3\text{N}_4$, CoMoO_4 and $\text{CoMoO}_4/\text{g-C}_3\text{N}_4$.

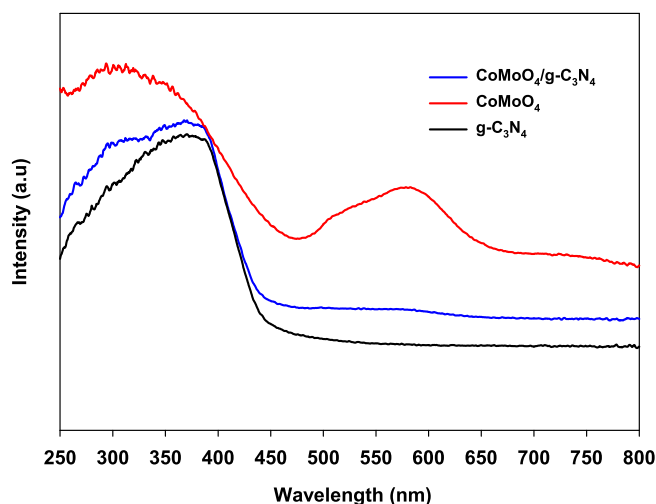


Fig. 4. UV-vis absorbance spectra of g-C₃N₄, CoMoO₄, and CoMoO₄/g-C₃N₄.

Table 1
Bandgap energy of photocatalyst.

Material	Band gap (eV)
g-C ₃ N ₄	2.71
CoMoO ₄	2.8
CoMoO ₄ /g-C ₃ N ₄	2.6

carbon nitride, indicating the formation of a heterojunction structure [19,21].

X-ray diffraction (XRD) was employed to investigate the crystal phase of g-C₃N₄, CoMoO₄, and CoMoO₄/g-C₃N₄ (Fig. 3). For g-C₃N₄, a sharp peak is observed at $2\theta = 27.4^\circ$, which is characteristic of the stacked arrangement of conjugated aromatic ring layers, similar to graphite (Fig. 3a). This angle corresponds to the (002) plane, as identified in previous studies [1,2,6,27,31–33]. Besides, a small peak is observed at $2\theta = 12.5^\circ$ corresponding to the (001) plane, which reflects the characteristic tri-s-triazine structure of graphitic carbon nitride. The X-ray diffraction pattern of CoMoO₄ reveals peaks at $2\theta = 14.12^\circ, 23.24^\circ, 26.48^\circ, 28.36^\circ, 33.91^\circ, 36.62^\circ, 38.7^\circ, 40.1^\circ, 41.42^\circ, \text{ and } 43.44^\circ$, which are characteristic of its monoclinic crystal structure (Fig. 3b) [22, 24–26]. Additionally, the XRD pattern of CoMoO₄/g-C₃N₄ shows a peak at $2\theta = 27.1^\circ$, associated with graphitic carbon nitride, and a peak at $2\theta = 33.91^\circ$, corresponding to CoMoO₄ (Fig. 3c). The finding indicates the successful combination of CoMoO₄ and graphitic carbon nitride, resulting in the formation of a heterojunction photocatalyst [19,21,28].

The Ultraviolet-Visible (UV-Vis) absorption spectra of g-C₃N₄, CoMoO₄, and the CoMoO₄/g-C₃N₄ heterojunction photocatalyst are presented in Fig. 4. These spectra highlight the optical properties and light absorption behavior of the photocatalysts at various wavelengths. The results showed that all samples (g-C₃N₄, CoMoO₄, and CoMoO₄/g-C₃N₄) effectively absorb light above 400 nm, demonstrating their ability to harness visible light. In addition, the CoMoO₄/g-C₃N₄ heterojunction photocatalyst displayed a more extensive light absorption range in the visible region compared to g-C₃N₄, highlighting its advantages in the degradation of A-TC [19,21,25]. Based on the Tauc plot (Fig. S1) and the calculation of band gap energy (Table 1), the lowest band gap energy is attributed to CoMoO₄/g-C₃N₄ (2.6 eV), followed by g-C₃N₄ (2.71 eV) and CoMoO₄ (2.8 eV). Therefore, the CoMoO₄/g-C₃N₄ heterojunction photocatalyst is expected to exhibit better performance in the photocatalytic degradation of A-TC pollutants compared to the individual g-C₃N₄ and CoMoO₄ photocatalysts [21,28].

To evaluate the electron-hole recombination rate of the synthesized photocatalysts, photoluminescence (PL) analysis was employed (Fig. S2). The CoMoO₄/g-C₃N₄ heterojunction photocatalyst exhibited

the lowest PL peak intensity, followed by g-C₃N₄ and CoMoO₄. Previous works have demonstrated that a lower intensity of the PL peak corresponds to higher electron-hole separation efficiency, which in turn enhances the photocatalytic decomposition of A-TC pollutants. The finding further confirms the benefits of our synthesized CoMoO₄/g-C₃N₄ heterojunction photocatalyst for the removal of A-TC [19,21,22,27,28].

3.2. Removal of A-TC

Under dark conditions (60 min), the removal efficiencies of A-TC using CoMoO₄/g-C₃N₄, g-C₃N₄, and CoMoO₄ are only around 10 %. However, the degradation efficiencies of A-TC at Co = 5 mg/L rapidly improved to 91.3 %, 68.7 %, and 57.9 % when using visible light-driven CoMoO₄/g-C₃N₄, g-C₃N₄, and CoMoO₄, respectively. The data presented in Fig. 5a demonstrate that the degradation efficiency of A-TC using CoMoO₄/g-C₃N₄ was 91.3 % at C₀ = 5 mg/L and decreased to 82.3 and 66.4 % at initial concentrations of 10 and 50 mg/L, respectively. The removal efficiency of A-TC using g-C₃N₄ also decreased from 68.7 % at an initial concentration of 5 mg/L to 47.1 % at 50 mg/L (Fig. 5b). In addition, CoMoO₄ photocatalyst displayed a similar trend, with the removal efficiency of A-TC dropping from 57.9 % to 36.1 % as the antibiotic concentration increased from 5 to 50 mg/L, respectively (Fig. 5c). This phenomenon can be explained by reduced light transmission and increased competition among A-TC molecules at high pollutant concentrations, as reported in previous studies [1,4,34–36]. CoMoO₄/g-C₃N₄ exhibited the highest removal performance of A-TC, confirming the benefits of the heterojunction photocatalyst for the removal of antibiotic pollutants [17,27,28]. To further evaluate the potential of CoMoO₄/g-C₃N₄, a comparative analysis of A-TC degradation performance was carried out using different photocatalysts (Text S2, Table S1).

Moreover, the removal of A-TC was investigated using a physical mixture of g-C₃N₄ and CoMoO₄, matching the ratio of the synthesized CoMoO₄/g-C₃N₄ sample (Fig. 5d). Under the same conditions, the degradation efficiencies of A-TC were slightly lower than those of g-C₃N₄ at pollutant concentrations of 5, 10, and 50 mg/L. This may be because physical mixing reduces the active sites by blocking the surface of the photocatalyst, creating non-reactive areas, and disrupting the individual light absorption properties of g-C₃N₄ and CoMoO₄. Nevertheless, physical mixing did not establish any interaction or contact between g-C₃N₄ and CoMoO₄, and thus, the efficient charge transfer between the two materials did not improve. The result further confirmed the advantages of the synthesized CoMoO₄/g-C₃N₄ over the physical mixture of the two catalysts. In addition, the blank A-TC samples without the presence of photocatalysts showed no change, demonstrating that the pollutant does not undergo self-degradation.

3.2.1. Degradation kinetics

The first-order kinetics of A-TC follow Eq. (2):

$$\ln \frac{C}{C_0} = -kt \quad (2)$$

where k (min^{−1}) is the rate constant, C_0 is the initial concentration of A-TC, and C is the concentration of A-TC at time t .

The data presented in Fig. 6 and Table 2 show the correlation between the A-TC degradation process and first-order kinetics, as well as the fitting parameters, including the rate constant (k) and the coefficient (R^2). The CoMoO₄/g-C₃N₄ heterojunction photocatalyst exhibits excellent rate constants, with high k values ranging from 0.0182 to 0.0088 min^{−1}. It indicates that CoMoO₄/g-C₃N₄ can efficiently decompose or degrade the A-TC pollutant. Besides, the results also show that g-C₃N₄ can remove A-TC more quickly than CoMoO₄ because it has higher rate constants under the same conditions. In addition, the high coefficients (R^2), ranging from 0.93 to 0.98, suggest that the photodegradation of A-TC using CoMoO₄/g-C₃N₄, g-C₃N₄, and CoMoO₄ follows a first-order

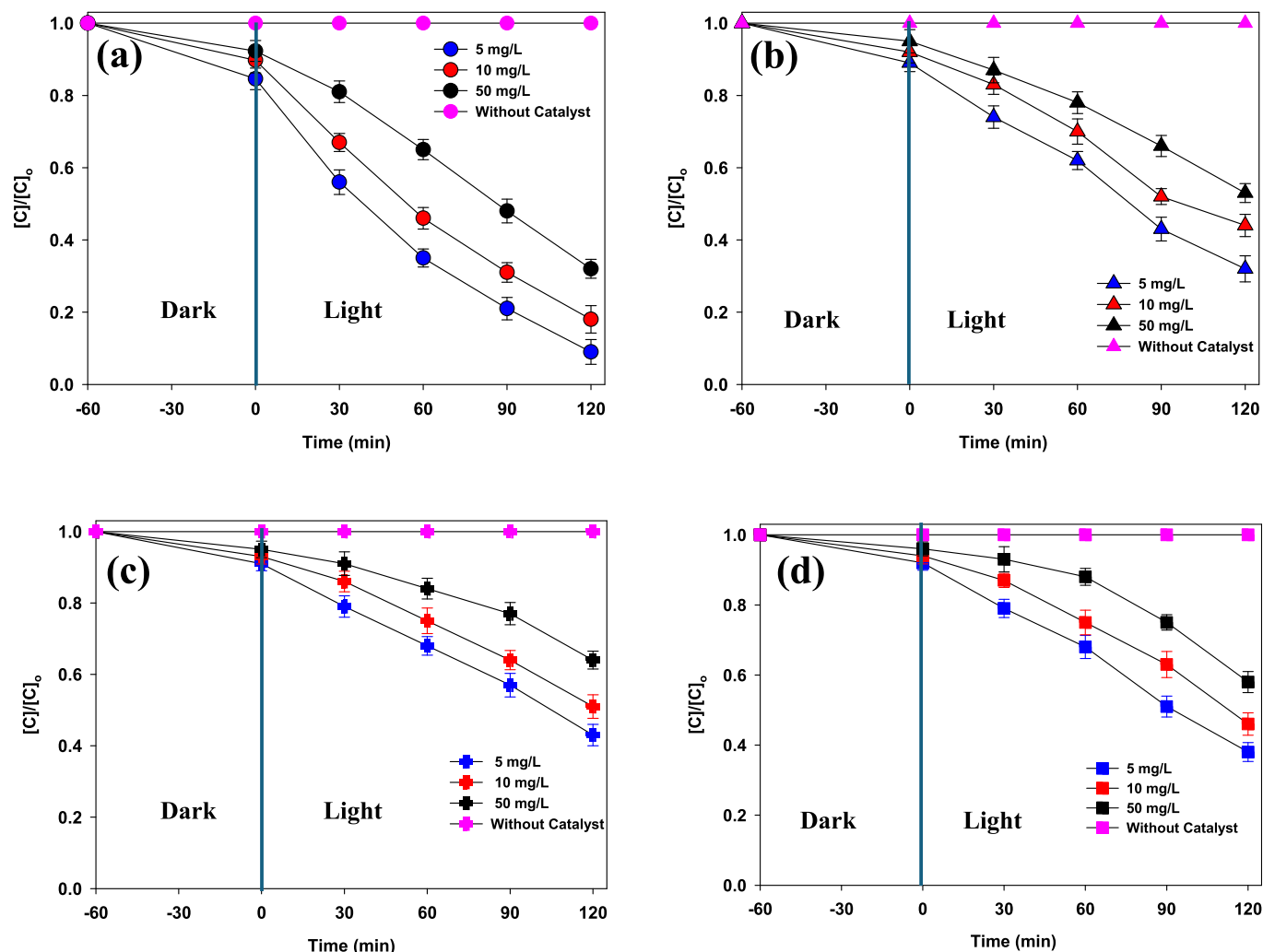


Fig. 5. Effect of initial concentration (a) CoMoO₄/g-C₃N₄, (b) g-C₃N₄, (c) CoMoO₄ and (d) physical mixture of (g-C₃N₄ + CoMoO₄) Condition: [A-TC] = 5–50 mg/L; pH = 6.0; m = 0.03g; V = 50 mL; Light source: Visible.

kinetic reaction [1,3,28].

3.2.2. Effect of coexisting pollutants

Wastewater samples often contain various contaminants, particularly when discharged from hospitals. It can include pharmaceutical residues, bacteria, and other organic substances [37–42]. The effects of inorganic substances (Cl^- , CO_3^{2-} , Na^+ , Mg^{2+}) and other antibiotic pollutants (oxytetracycline (O-TC) and ciprofloxacin (CF)) on the photodegradation of A-TC were evaluated, as shown in Fig. 7. It reveals that inorganic substances do not significantly impact the removal efficiency of A-TC. In other words, the CoMoO₄/g-C₃N₄ heterojunction photocatalyst used in the study can effectively remove A-TC pollutants in the presence of inorganic anions or cations.

Besides, the addition of the CO_3^{2-} anion slightly enhanced the removal performance of A-TC due to the formation of $\text{OH}^\cdot$ through the reaction ($\text{CO}_3^{2-} + \text{H}_2\text{O} \rightleftharpoons \text{HCO}_3^- + \text{OH}^\cdot$), which can generate more hydroxyl radicals to oxidize antibiotic pollutants [1,2]. However, the situation is different in the presence of organic pollutants, such as CF and O-TC, which significantly influence the removal performance of A-TC [9,26–28].

For example, the degradation efficiency of A-TC using CoMoO₄/g-C₃N₄ decreases to 82.3 % and 86.8 % in the presence of O-TC and CF, respectively. This can be explained by the competition between other antibiotic pollutants and A-TC for interaction with the photocatalytic material, leading to a reduction in degradation efficiency. This result is

also consistent with previous studies on the impact of coexisting organic pollutants on the photodegradation of A-TC [2–4,26,27].

3.2.3. Removal of A-TC in wastewater

To explore the practical application of CoMoO₄/g-C₃N₄, the removal of A-TC from the wastewater sample was evaluated. The key parameters of the wastewater sample are provided in the supporting information (Table S2). As shown in Fig. 8a, the degradation efficiencies of A-TC using CoMoO₄/g-C₃N₄ were 29.3, 50.1, 65.3, and 80.2 % at reaction times of 30, 60, 90, and 120 min, respectively. The removal performance of A-TC in wastewater was slightly reduced compared to its performance in an aqueous solution. This is due to the effect of other pollutants present in the wastewater sample. However, the removal performance of A-TC remains high (over 80 %), confirming the potential of CoMoO₄/g-C₃N₄ for the degradation of antibiotic pollutants.

3.2.4. Reusability of CoMoO₄/g-C₃N₄ heterojunction photocatalyst

The reusability of the CoMoO₄/g-C₃N₄ heterojunction photocatalyst was evaluated through four repeated A-TC degradation experiments, and the results are shown in Fig. 8b. The degradation efficiency of A-TC decreased to 72.3, 67.4, and 54.7 % in the second, third, and fourth cycles, respectively. The decline in photocatalytic performance can be attributed to the loss of CoMoO₄/g-C₃N₄ during the processes of separation, washing, and drying [2–5,26–29]. Nevertheless, the CoMoO₄/g-C₃N₄ photocatalyst can be effectively reused for at least two

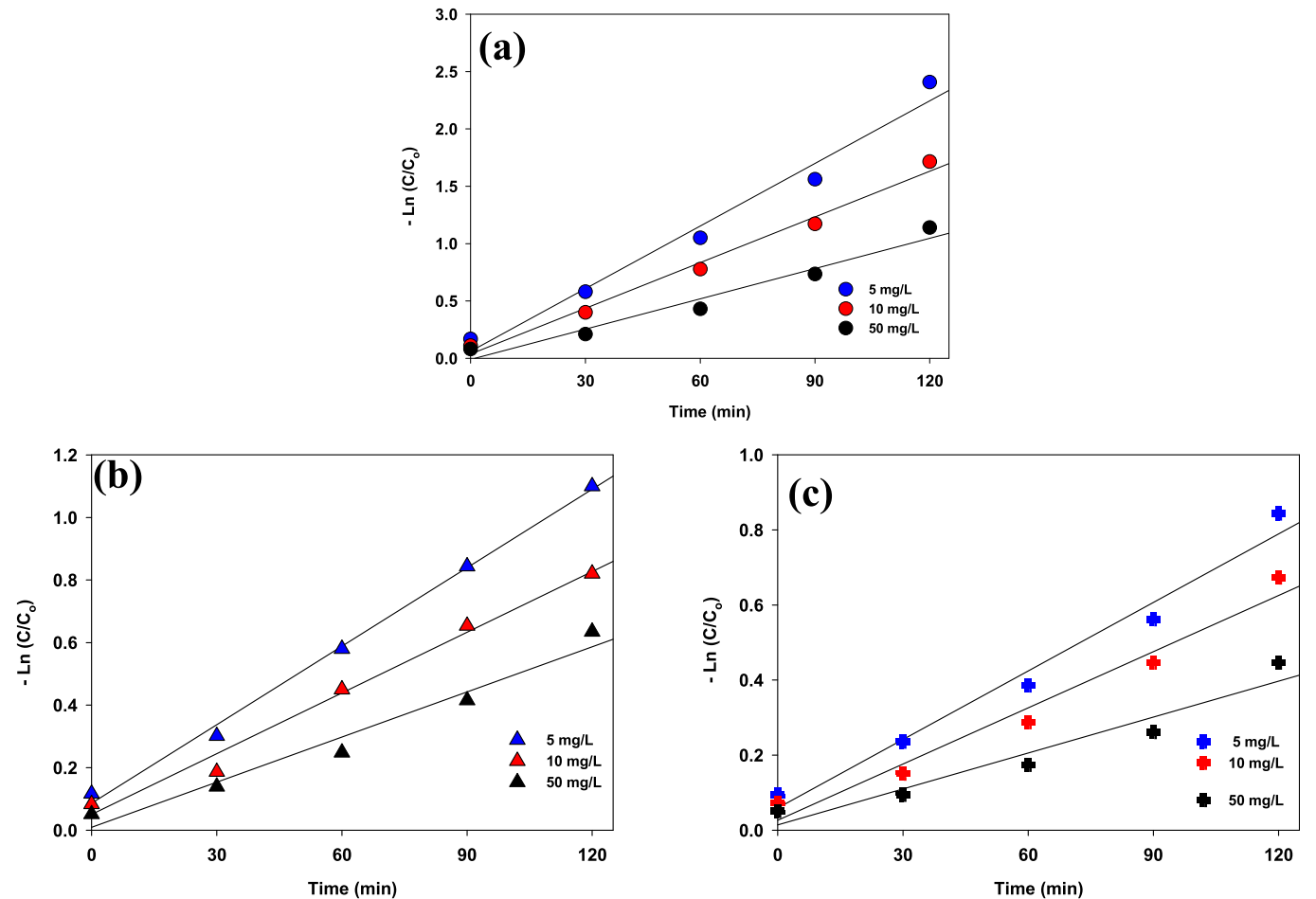


Fig. 6. Degradation kinetics (a) CoMoO₄/g-C₃N₄, (b) g-C₃N₄ and (c) CoMoO₄. Condition: [A-TC] = 5–50 mg/L; pH = 6.0; m = 0.03g; V = 50 mL; Light source: Visible.

Table 2
Fitting parameters for degradation kinetics of A-TC under different concentrations.

Catalyst	Concentration (Co - mg/L)	Degradation rate (k - min ⁻¹)	Correlation coefficient (R ²)
CoMoO ₄	5	0.0061	0.97
	10	0.005	0.96
	50	0.0032	0.93
g-C ₃ N ₄	5	0.0086	0.97
	10	0.0065	0.97
	50	0.0048	0.96
CoMoO ₄ /g-C ₃ N ₄	5	0.0182	0.97
	10	0.0133	0.98
	50	0.0088	0.96

cycles, maintaining the A-TC removal efficiency above 72 %.

3.2.5. Degradation mechanism of A-TC using CoMoO₄/g-C₃N₄

3.2.5.1. Confirmation of radical species. To investigate the radicals that existed during the photodegradation of A-TC using CoMoO₄/g-C₃N₄, the quenching test was employed (Fig. 9). The quenchers including isopropanol (IPA), 1,4-benzoquinone (BQ), and Ethylenediaminetetraacetic acid (EDTA) were applied to inhibit the reactivity of •OH, •O₂⁻, and h⁺, respectively [1,29].

The degradation efficiency of A-TC using CoMoO₄/g-C₃N₄ reduced to 33.6, 54.2 and 75.8 % in the presence of IPA, BQ, and EDTA, respectively. The results suggest that h⁺, •OH and •O₂⁻ radicals contribute to

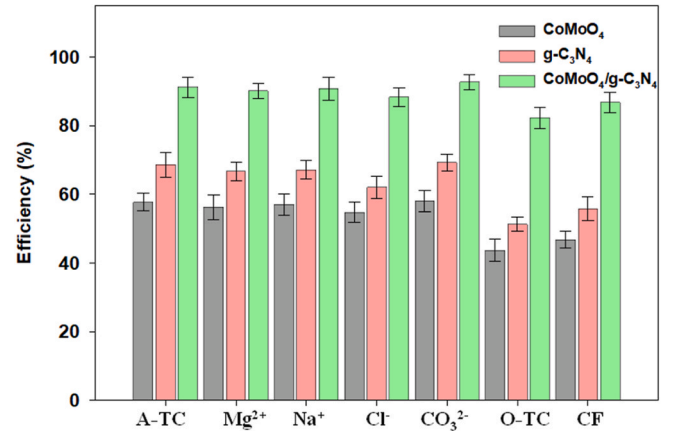


Fig. 7. Effect of coexisting pollutants on photodegradation of A-TC. Condition: [A-TC] = 5 mg/L; [O-TC] = [CF] = [Cl⁻] = [Mg²⁺] = [Na⁺] = [CO₃²⁻] = 2 mg/L; pH = 6.0; m = 0.03g; V = 50 mL; Light source: Visible.

the degradation of A-TC, with •OH and •O₂⁻ radicals are main contributors [19,22]. In addition, electron spin resonance (ESR) analysis was performed to confirm the presence of hydroxyl radicals (Fig. S3).

3.2.5.2. Total organic carbon removal. On the other hand, after 120 min of contact time, the total organic carbon was reduced by 96.4 %, 68.7 %, and 57.9 % using CoMoO₄/g-C₃N₄, g-C₃N₄, and CoMoO₄, respectively

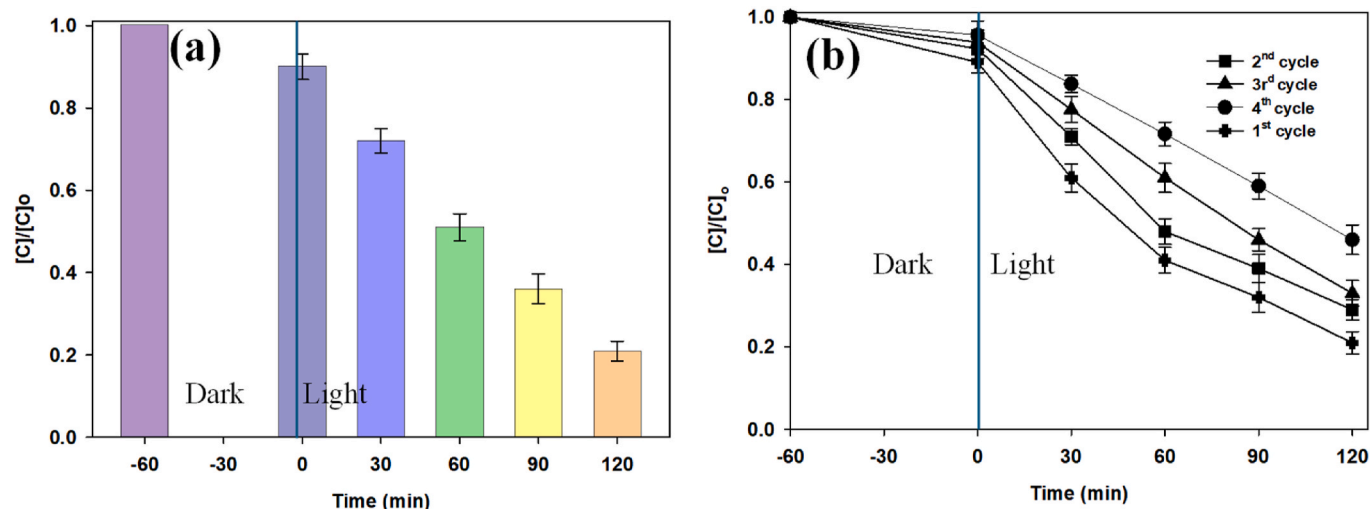


Fig. 8. Removal of A-TC from wastewater sample (a) and recycling of CoMoO₄/g-C₃N₄ (b)
Condition: [A-TC] = 6.87 mg/L; pH = 6.75; m = 0.03 g; V = 50 mL; Light source: Visible light.

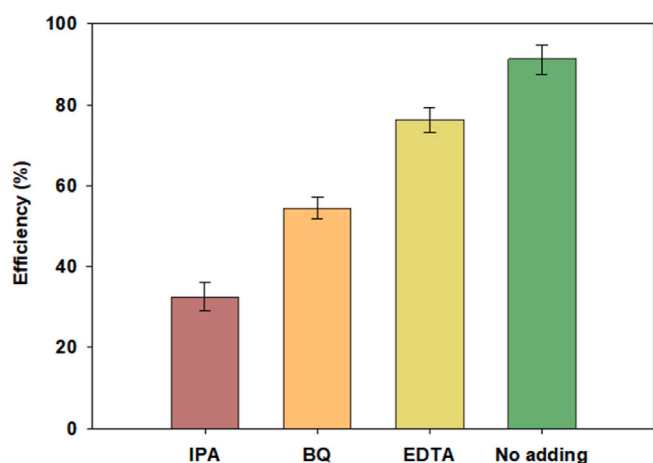


Fig. 9. Effect of radicals on photodegradation of A-TC.

(Fig. S4). The result suggests that A-TC and its by-products were converted into inorganic compounds during the photodegradation process. The observed result is consistent with previous works on the degradation of organic pollutants using photocatalysts [4–6,31–33,35,36,43,44].

3.2.5.3. Determination of the conduction band and valence band potentials. To confirm the Z-scheme mechanism, Mott-Schottky plots were employed to determine the conduction band (E_{CB}) and valence band (E_{VB}) potentials of CoMoO₄ and g-C₃N₄ (Text S3, Fig. S5, and Table S3).

3.2.5.4. Proposed mechanism. Based on the results of radical quenching, total organic carbon reduction, and Mott-Schottky analysis, the degradation of A-TC using CoMoO₄/g-C₃N₄ is likely to follow a Z-scheme mechanism [6,19,25,27,28,36,44]. Firstly, under light irradiation, electrons in the valence band of both CoMoO₄ and g-C₃N₄ are excited and move to the conduction band, leaving the holes in the valence band [4–6,31,33,35,43,44]. Secondly, the electrons in the conduction band of CoMoO₄ preferentially recombine with the holes in the valence band of g-C₃N₄ [31,35]. As a result, the electrons in the conduction band of g-C₃N₄ and the holes in the valence band of CoMoO₄ are effectively separated. Thirdly, the electrons from the conduction band of g-C₃N₄

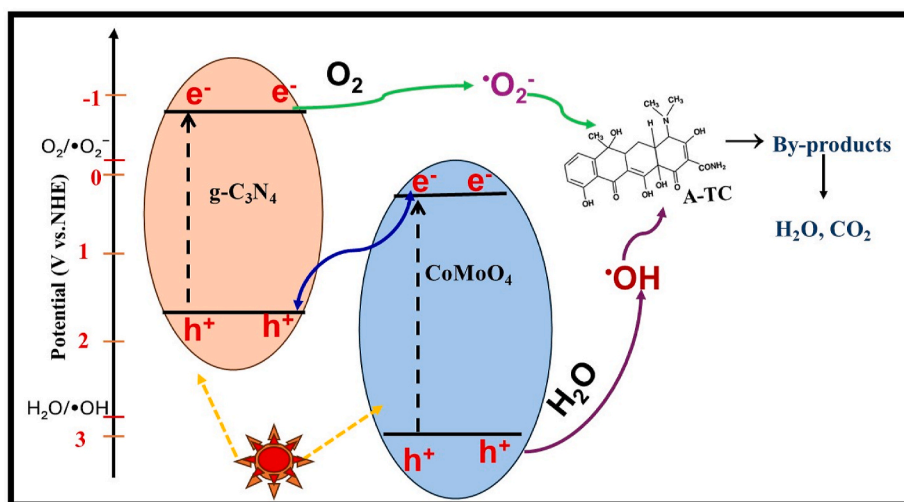


Fig. 10. Degradation mechanism of A-TC using CoMoO₄/g-C₃N₄ heterojunction photocatalyst.

react with oxygen to form $\bullet\text{O}_2^-$ radicals, while the holes in the valence band of CoMoO_4 interact with water to generate $\bullet\text{OH}$ radicals [36,43]. Finally, the radicals ($\bullet\text{OH}$ and $\bullet\text{O}_2^-$) degrade A-TC into intermediate products, which are then broken down into inorganic substances, including water and carbon dioxide (Fig. 10) [6,25,27,28,35,43].

4. Conclusion

In this work, $\text{CoMoO}_4/\text{g-C}_3\text{N}_4$ heterojunction photocatalyst was successfully prepared to degrade the A-TC antibiotic from wastewater. With a low bandgap energy of 2.6 eV and an excellent electron-hole separation rate, $\text{CoMoO}_4/\text{g-C}_3\text{N}_4$ heterojunction photocatalyst exhibited higher degradation efficiency for A-TC compared to individual CoMoO_4 and $\text{g-C}_3\text{N}_4$ material. The removal efficiencies of A-TC using $\text{g-C}_3\text{N}_4$, CoMoO_4 , and $\text{CoMoO}_4/\text{g-C}_3\text{N}_4$ were 68.7 %, 57.9 %, and 91.3 %, respectively. Besides, $\text{CoMoO}_4/\text{g-C}_3\text{N}_4$ heterojunction photocatalyst was able to decompose 80.2 % of A-TC from wastewater and retained high degradation performance (over 72 %) after two reuse cycles. In addition, the proposed mechanism for the degradation of A-TC using the $\text{CoMoO}_4/\text{g-C}_3\text{N}_4$ heterojunction photocatalyst was discussed based on a Z-scheme mechanism and the main roles of $\bullet\text{OH}$ and $\bullet\text{O}_2^-$ radicals.

CRediT authorship contribution statement

Kim Jitae: Writing – original draft, Methodology, Investigation, Formal analysis. **Minh Viet Nguyen:** Methodology, Formal analysis, Data curation, Conceptualization. **Pham Thi Huong:** Writing – review & editing, Supervision, Investigation.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.matchemphys.2025.130433>

Data availability

The data that has been used is confidential.

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