



Enhanced removal of antibiotic residues from wastewater using metal-doped TiO_2 : mitigating the potential risk of antibiotic-resistant bacteria to human health

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Abstract The impact of antibiotic residues on human health and the environment has become a serious global concern. Scientists are developing new technologies to remove antibiotic pollutants from water, wastewater, and soil. This study presents an effective method for removing antibiotic residues from sewage using Cu-doped TiO_2 photocatalyst (Cu-TiO_2). Ciprofloxacin antibiotic residue (CFA) was selected as the model pollutant for this investigation due to its common use in the healthcare system. The result showed that Cu-TiO_2 effectively removes

94.1% and 85.7% of CFA from wastewater under solar and visible light, respectively. According to the Langmuir–Hinshelwood model, Cu-TiO_2 degrades CFA faster than TiO_2 , with a half-life of 14.7 min, whereas TiO_2 has a half-life of over 69 min. Besides, the doped photocatalyst also presented high reusability, retaining 74.6% CFA degradation efficiency after five cycles and releasing less than 1.8% of Cu ions. Furthermore, this study investigated the effectiveness of the Cu-TiO_2 photocatalyst in mitigating health risks associated with antibiotic-resistant bacteria and evaluated its practical application.

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Introduction

Natural disasters, such as storms, tornadoes, heat-waves, and floods, seem to be occurring more frequently and with greater intensity (Sapkota & Kotanko, 2023; Wang et al., 2025a, 2025b). In addition, epidemics such as influenza, respiratory diseases, Ebola, and Zika appear more and more frequently, spreading rapidly and causing serious impacts on social life as well as human health. Water pollution makes it more difficult to find clean water, which could soon become a crisis in the near future (Bhatt et al., 2025; Javan et al., 2025). Scientists

around the world have observed that new diseases are emerging and being developed, with the potential to spread more rapidly, possibly due to the presence of genetically modified bacteria. This leads to increasingly complex treatment, placing considerable pressure on the medical sector. Therefore, finding effective ways to reduce excess antibiotic residues in the environment or convert them into harmless compounds has been and continues to be a key focus of research (Mishra et al., 2026; Pagaling et al., 2023; Savin et al., 2021). Figure 1 illustrates commonly used antibiotics, categorized by chemical structure and application.

Ciprofloxacin is a powerful antibiotic often used to treat many types of bacterial infections, including those of the urinary tract, lungs, stomach and intestines, skin, and some sexually transmitted diseases. However, it also has significant drawbacks and side effects, including prolonged exposure to the environment and harm to aquatic animals. It is often found in hospital wastewater, city sewage, and in rivers and lakes (Diao et al., 2025; Gupta et al., 2025; Kim et al., 2025; Mishra et al., 2026; Rodríguez-López

et al., 2024; Rodríguez-Ruiz et al., 2024; Roth et al., 2025; Wang et al., 2025a, 2025b). One of the main problems with antibiotics is that they can lead to antibiotic-resistant genes and bacteria, which are very dangerous and have wide-ranging effects. Research shows that antibiotic resistance affects not just people but also creates serious challenges for health organizations and healthcare systems. Antibiotic pollution in the environment, found in rivers, lakes, and oceans around the world, has also raised concerns about its impact on ecosystems (Behere et al., 2025; Cocker et al., 2025; Daisley et al., 2025; Matubber et al., 2025; Pagaling et al., 2023; Song et al., 2025; Vilca et al., 2025; Wang et al., 2025a, 2025b; Zhao et al., 2024, 2025). For example, most antibiotic pollution can persist in the environment for a long time, mix with natural systems, and help create new strains of bacteria that drugs cannot kill. Also, these drug-resistant bacteria keep appearing, get into animals and plants, and then move back to humans through food chains.

Table 1 lists the main sources of antibiotic residues found in the environment. The pharmaceutical

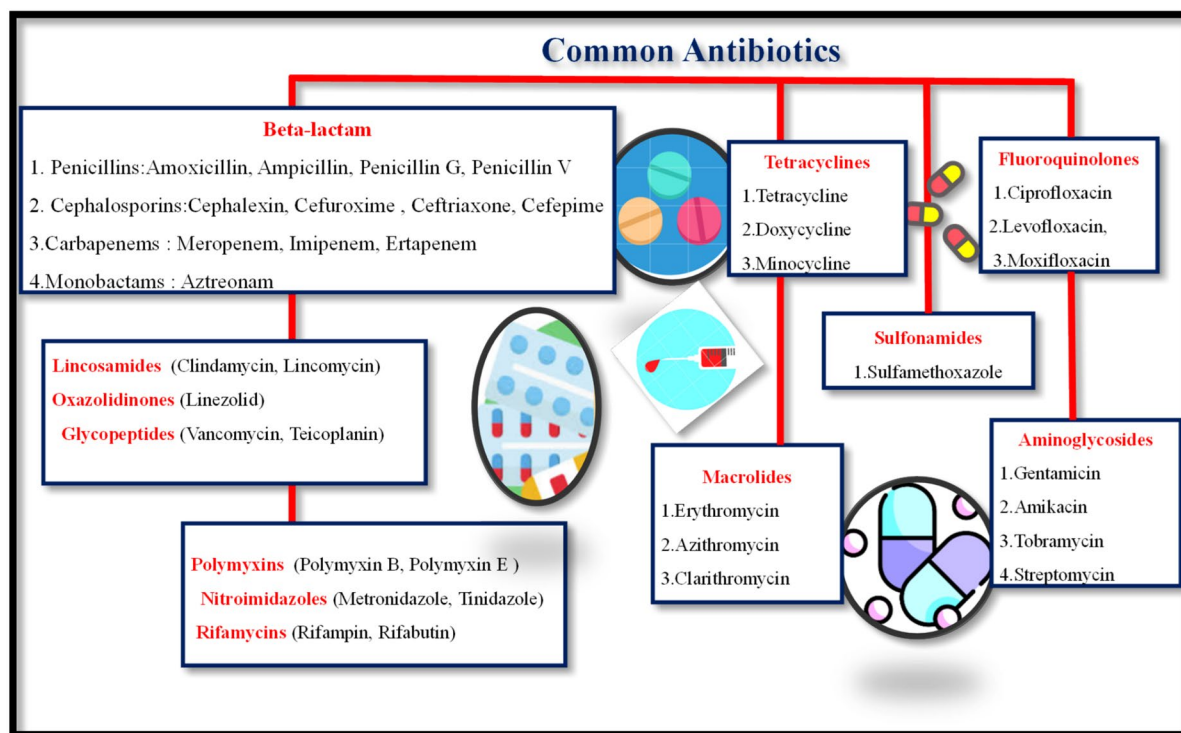


Fig. 1 Major classes of antibiotics

Table 1 Main sources responsible for discharging antibiotic residues

Source	Reason for antibiotic residue	Pathway
Pharmaceutical Industry	Manufacturing waste, poor effluent treatment	Discharge to water, landfills
Hospitals	Human excretion, improper disposal	Wastewater → Incomplete treatment → Discharge into water bodies or leakage into soil
Households	Unused/expired drugs, excretion	Flushing, waste → landfills, sewage
Veterinary Use	Animal excretion, manure, and aquaculture	Runoff, leaching, and direct release to water bodies

industry, hospitals, households, and veterinary medicine are the main contributors. The global antibiotics market grew from \$11.9 billion in 2009 to \$84.68 billion in 2024 and is expected to reach \$110.65 billion by 2029. This growth shows a sharp increase in antibiotic use worldwide, as healthcare needs and practices expand for both people and animals. Because it produces large amounts each year to meet demand, the pharmaceutical industry is seen as a major source of antibiotic emissions (Daisley et al., 2025; Izah et al., 2025; Pagaling et al., 2023; Savin et al., 2021).

Hospitals and health systems account for a significant share of antibiotic use because they treat numerous infections. After people take these antibiotics, between 30 and 90% of the drug is not fully broken down in the body and is excreted, mainly in urine. If hospital antibiotic residues are not properly treated or controlled, they can enter wastewater systems and become a major source of pharmaceutical pollution in nearby ecosystems and the environment. Additionally, when expired or unused drugs are disposed of incorrectly, they are more likely to end up in water or soil. (Chi et al., 2025; Niu et al., 2025).

In many countries, especially in developing and low-income areas, people can get antibiotics easily, sometimes without a prescription. Many use these drugs without proper guidance and often get rid of unused or expired antibiotics by flushing them down the toilet, which allows large amounts to enter the environment. Antibiotics are also widely used in the raising of livestock, poultry, and fish to prevent disease, treat illnesses, and promote growth. Animals then excrete much of these antibiotics in their urine and feces, which leads to significant amounts of antibiotic residues ending up in water and soil (Behere et al., 2025; Cocker et al., 2025; Izah et al., 2025; Pagaling et al., 2023; Savin et al., 2021; Tiwari et al., 2025; Wang et al., 2025a, 2025b).

Controlling and removing antibiotic residues helps prevent the development of new bacterial strains and protects both the environment and human health. However, common wastewater treatment processes often do not remove all ciprofloxacin, so it can persist in natural water and may spread antibiotic resistance genes.

TiO₂-based advanced oxidation processes can effectively break down organic pollutants like CFA and reduce their impact on the environment (Hamid & Khanday, 2026; Jang et al., 2025; Li et al., 2018). TiO₂ is often used due to its popularity, low toxicity, and high efficiency. When exposed to UV light, TiO₂ creates reactive species that can directly attack and degrade antibiotic pollutants (Ahmad et al., 2024; Khan & Shah, 2023). However, it still faces various challenges, such as high energy use, the need for UV light, and rapid electron–hole recombination.

Previous studies have shown that doping metals such as Ni, Cu, Fe, Pt, Ag, Au, La, and Ce into TiO₂ can enhance its photocatalytic properties (Gupta et al., 2025; Kim & Lee, 2018; Mayoufi et al., 2014; Rachna et al., 2019; Sukhadeve et al., 2023). Cu is a transition metal that is highly conductive, low-cost, and relatively harmless. Besides, Cu is an essential nutrient for humans, animals, plants, and microbes (Huong et al., 2024; Kim & Lee, 2018; Muñoz et al., 2024). Therefore, it is both effective and more environmentally friendly than other metals and can be considered a potential dopant to enhance the photocatalytic activity of TiO₂. Hence, this work investigates the potential application of Cu-doped TiO₂ for removing antibiotic residues from hospital wastewater. It combines the strong oxidative power, stability, and low cost of TiO₂ with the improved visible-light absorption and better charge separation provided by Cu species. The combined effect of TiO₂ and Cu leads to more efficient generation of reactive species such as hydroxyl radicals

and superoxide anion radicals. Therefore, Cu-TiO₂ could enhance the degradation of CFA and other organic pollutants, offering an effective method for treating wastewater from hospitals and healthcare centers.

The Cu-TiO₂ photocatalyst was characterized and then used to remove ciprofloxacin from wastewater. The effects of different experimental conditions, such as initial concentrations, coexisting compounds, and light sources, were examined. Besides, the degradation kinetics, reusability, and removal mechanism were also studied. In addition, the evaluation of Cu-TiO₂ for the treatment of antibiotic residues, including comparisons with other materials, cost-effectiveness, and potential scale-up, was discussed.

Materials and methods

Synthesis and characterization of catalysts

The Synthesis of Cu-TiO₂ by impregnation is as follows: 20 g of TiO₂ (purchased from Sigma-Aldrich) was dispersed in a solvent mixture of deionized water (70 vol%) and ethanol (30 vol%). Copper(II) nitrate trihydrate [Cu(NO₃)₂·3H₂O] was added to the suspension to obtain Cu loadings of 0.5, 1, 3, 5, 7, and 10 wt% with respect to TiO₂. The mixture was sonicated and stirred in an ultrasonic bath for 30 min to ensure homogeneous distribution of Cu precursor. The resulting suspension was dried in an oven at 80 °C for 48 h, followed by calcination at 450 °C for 2 h under nitrogen gas.

The obtained catalysts were denoted according to their Cu loading as 0.5Cu-TiO₂, 1Cu-TiO₂, 3Cu-TiO₂, 5Cu-TiO₂, 7Cu-TiO₂, and 10Cu-TiO₂. To determine the optimal Cu content, these samples were used for the photocatalytic removal of CFA under solar irradiation (Text S1, Fig. S1).

Characterization of catalysts

To identify the photochemical and photocatalytic properties of Cu-TiO₂, various characterization techniques were employed (Supporting material, Text S2).

Degradation of CFA antibiotic residue

The degradation of CFA using TiO₂ and Cu-TiO₂ catalysts was examined in a quartz reactor with a catalyst mass of 0.05 g. The degradation experiments were irradiated with a 300 W Xe lamp to simulate solar light, and a 420 nm cutoff filter was used to provide visible light. The effect of initial concentration on the photodegradation of CFA was investigated in the range of 1–10 mg L⁻¹. Moreover, the solution pH was adjusted from 4.0 to 8.0 to examine the relationship between pH and CFA removal performance. The influence of coexisting pollutants and ions, specifically Cl⁻, Na⁺, tetracycline (TC), and ofloxacin (OF), each at 2 mL and 0.5 mg L⁻¹, was examined. The transformation of CFA during photodegradation was confirmed by LC-MS analysis and by measuring reductions in total organic carbon (TOC). Besides, hydroxyl radicals (•OH), superoxide radicals (O₂•⁻), and holes (h⁺) were detected using the specific scavengers ethanol (EtOH), p-benzoquinone (p-BQ), and ethylenediaminetetraacetic acid (EDTA), respectively. CFA degradation kinetics were investigated using first-order and Langmuir-Hinshelwood (L-H) models. The reusability of Cu-TiO₂ and the release of Cu ions were evaluated over five consecutive degradation cycles. On the other hand, the removal of CFA from hospital wastewater (Text S4) was evaluated by adding 0.05 g of Cu-TiO₂ to 100 mL of the wastewater sample, stirring in the dark for 30 min, followed by 120 min of light irradiation. 2 mL aliquot was withdrawn, filtered, and analyzed every 30 min to measure the remaining CFA concentration. All experiments were conducted in duplicate, and mean values are reported. The photodegradation efficiency and the reduction in total organic carbon (TOC) were determined using Eqs. (1) and (2), respectively.

$$E(\%) = [(C_0 - C)/C_0] \times 100 \quad (1)$$

$$R_{\text{TOC}}(\%) = [(TOC_0 - TOC)/TOC_0] \times 100 \quad (2)$$

where E is the degradation efficiency of CFA; C₀ and C are the initial and final concentrations of the antibiotic, respectively; R_{TOC} is the total organic carbon reduction efficiency; and TOC₀ and TOC are the initial and final total organic carbon values, respectively.

Results and discussion

Properties of photocatalysts

SEM and TEM analysis

Figure S2 (a–b) presents the surface morphologies of TiO_2 before and after Cu doping. The original catalyst is composed of nearly spherical nanoparticles with a uniform size distribution that aggregate into cluster-like structures, as observed in the TEM image (Fig. S2c). However, Cu-TiO_2 exhibits a slightly different surface morphology compared with the undoped catalyst. Figure S2b shows the appearance of other particles on the TiO_2 surface, confirming the loading of Cu onto the catalyst. Further, the TEM image of Cu-TiO_2 displays small particles together in denser, darker clusters (Fig. S2d). Compared to the TEM result of the undoped sample, Cu-TiO_2 exhibits more mass and is thicker than the undoped catalyst.

XRD analysis

Figure 2a shows the undoped catalyst (TiO_2), exhibiting characteristic peaks at $2\theta \approx 25.3^\circ$ (101), 37.8° (004), 48.0° (200), 53.9° (105), 55.1° (211), 62.7° (204), 68.8° (116), 70.3° (220), and 75.0° (215), confirming single-phase anatase with high crystallinity (Chen et al., 2023; Gupta et al., 2025; Kim & Lee, 2018; Mayoufi et al., 2014; Motlagh et al., 2021). The

XRD pattern of Cu-TiO_2 in Fig. 2b is quite similar to that of the TiO_2 sample. However, new peaks at $2\theta = 38.1^\circ$ and 48.7° appeared, confirming the presence of CuO (Kim & Lee, 2018).

UV-vis and PL analysis

Figure S3 shows the light absorption and photoluminescence (PL) behavior of the catalysts, obtained from UV-vis and PL analyses, respectively. The results in Figure S3a indicate that, after Cu doping, light absorption extends into the visible region, while the undoped TiO_2 mainly absorbs in the UV (Parmar & Srivastava, 2022). Besides, the Tauc plot (insert of Fig. S3a) reveals that the band gap energy decreases from 3.1 to 2.7 eV upon Cu modification.

Figure S3b shows the high PL intensity of TiO_2 photocatalyst, suggesting it may have a rapid electron-hole recombination rate during the photoreaction. However, the PL intensity of Cu-TiO_2 is significantly reduced, confirming better charge-separation performance. This behavior can be explained by the role of Cu in the doped catalyst, which acts as an electron acceptor (Kim & Lee, 2018; Zhang et al., 2024a, 2024b). The characterization results demonstrate that the optical properties and the separation of electron-hole pairs are significantly enhanced after Cu doping. Therefore, Cu-TiO_2 is expected to offer higher photocatalytic degradation efficiency of CFA.

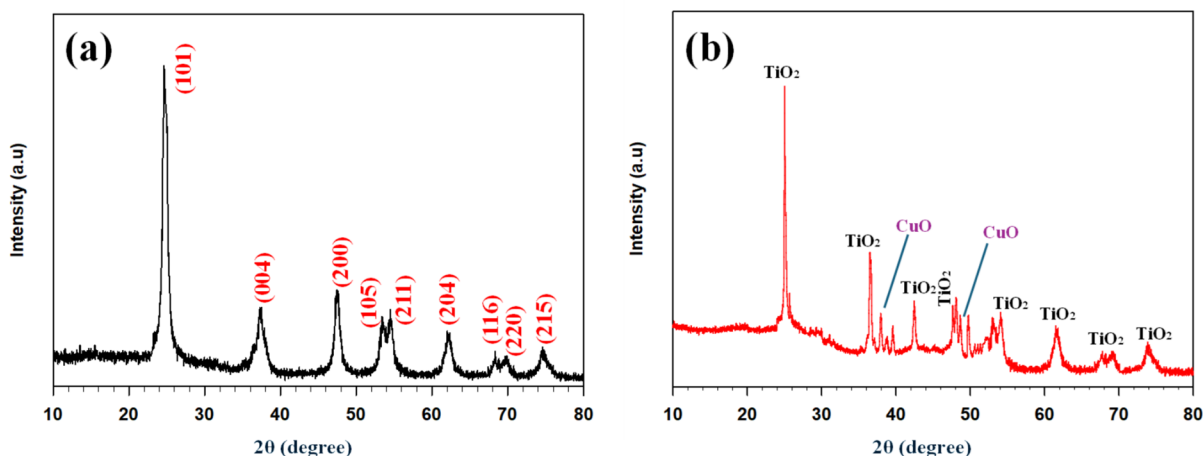


Fig. 2 XRD pattern of **a** TiO_2 and **b** Cu-TiO_2

Degradation of CFA

Effect of initial concentration

Figure 3 presents the influence of antibiotic contaminant concentration on CFA removal using TiO_2 and Cu-TiO_2 photocatalysts. CFA removal efficiency was higher at lower contaminant concentrations and declined as concentrations increased. For example, the removal efficiency of CFA using TiO_2 decreased from 68.3% to 54.1% as the initial concentration rose from 1 to 10 mg/L. Cu-TiO_2 also exhibited a similar trend to the undoped sample, with CFA degradation of 100% at 1 mg L^{-1} , decreasing to 95.6% at 10 mg L^{-1} . Previous studies have attributed the reduced degradation efficiency of antibiotics at higher concentrations to factors such as diminished light transmission, limited interaction between light and photocatalytic materials, saturation of active sites on the catalyst surface, and competition between intermediate products and free radicals (Jang et al., 2025; Lyu et al., 2026). The results show that Cu-modified TiO_2 significantly improves the photodegradation efficiency of CFA. This phenomenon may be due to changes in the optical properties of the original catalyst and the role of Cu (as an electron trap), resulting in inhibition of the electron–hole recombination rate. Once electron–hole pairs are separated, they can effectively react with oxygen and water to form reactive radicals that directly break down the CFA pollutant (Etafa Tasisa et al., 2024; Gupta et al., 2025; Jang et al.,

2025; Nasr et al., 2019; Sukhadeve & Gedam, 2023; Sukhadeve et al., 2023).

Degradation kinetics

The first-order kinetic model and the Langmuir–Hinshelwood (L–H) model were used to describe the interaction of the photocatalysts (TiO_2 and Cu-TiO_2) with the CFA antibiotic pollutant. Figure 4 presents the first-order kinetics of CFA degradation, and Table 2 provides the parameters for both kinetic models. As the initial concentration increases, the CFA degradation rate decreases, consistent with the observed changes in degradation efficiency. Besides, the coefficient (R^2) displayed close to 1 (0.95 to 0.99), suggesting photodegradation of CFA followed the first-order kinetic model (Gupta et al., 2025; Mayoufi et al., 2014; Sukhadeve & Gedam, 2023). The L–H model describes the reaction mechanism occurring at the photocatalyst surface and the interactions between TiO_2 or Cu-TiO_2 and CFA. Further, Table 2 reports the time required ($t_{1/2}$) for TiO_2 and Cu-TiO_2 to decompose 50% of the CFA antibiotic. As a result, Cu-TiO_2 requires less time to decompose CFA than TiO_2 at both low and high levels of antibiotic pollutants. For example, the time necessary to remove 50% of CFA (10 mg/L) was 69.3 min with TiO_2 and 14.7 min with Cu-TiO_2 . This finding further confirms the improvement in photocatalytic activity after doping, as well as the benefit of Cu-TiO_2 in reducing degradation time. Moreover, Cu-TiO_2 catalyst also

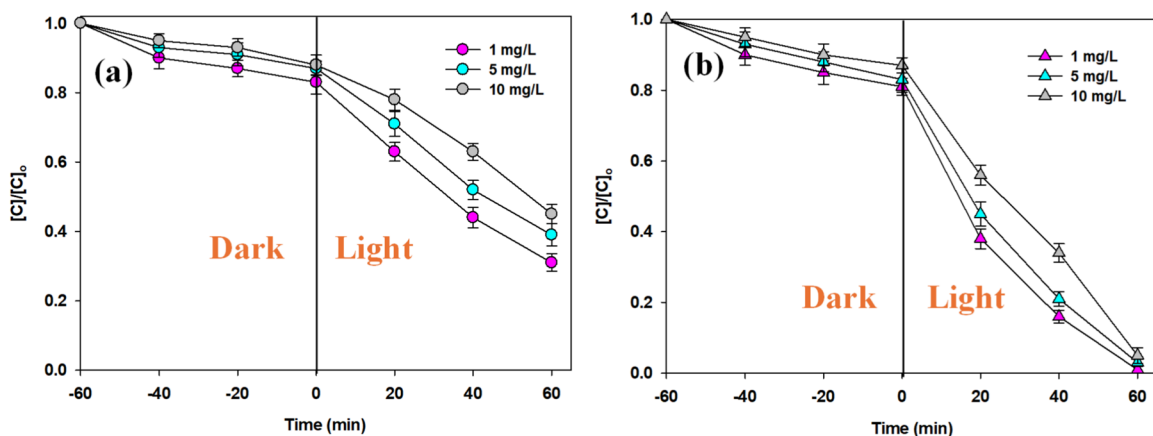


Fig. 3 Effect of initial concentration on CFA removal using **a** TiO_2 and **b** Cu-TiO_2

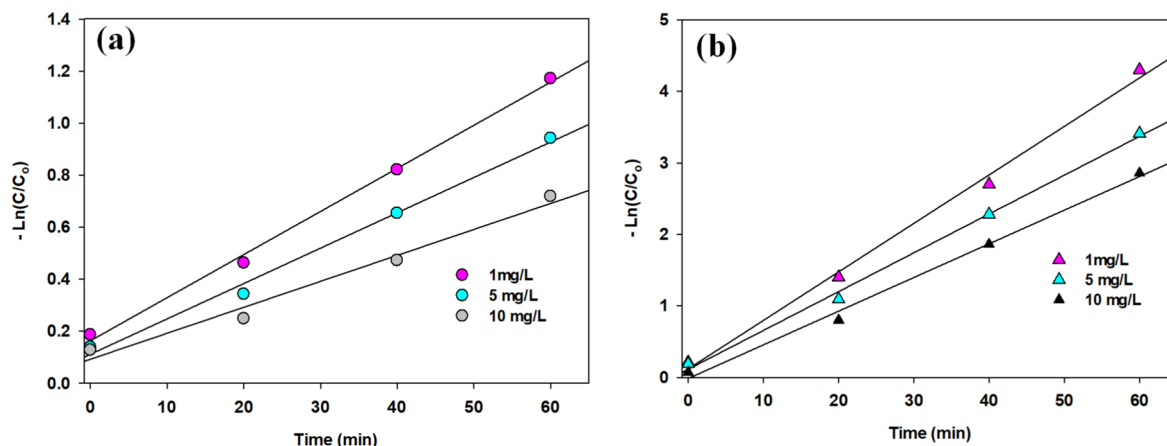


Fig. 4 First-order kinetics during degradation of CFA using **a** TiO_2 and **b** Cu-TiO_2

Table 2 Kinetic parameters during degradation of CFA using TiO_2 and Cu-TiO_2

Catalyst	First-order model			Langmuir–Hinshelwood
	C_0 (mg L^{-1})	k (min^{-1})	R^2	$t_{1/2}$ (min)
TiO_2	1	0.0166	0.99	41.8
	5	0.0136	0.99	51.0
	10	0.010	0.97	69.3
Cu-TiO_2	1	0.072	0.96	9.6
	5	0.054	0.96	12.8
	10	0.047	0.95	14.7

TiO_2 ($k_{\text{LH}}=0.0224 \text{ mg L}^{-1} \text{ min}^{-1}$; $K_{\text{L}}=0.82 \text{ L mg}^{-1}$); Cu-TiO_2 ($k_{\text{LH}}=0.1235 \text{ mg L}^{-1} \text{ min}^{-1}$; $K_{\text{L}}=0.60 \text{ L mg}^{-1}$)

exhibits a significantly higher intrinsic reaction rate constant than TiO_2 , suggesting Cu doping enhances charge separation and radical formation, resulting in an increased photodegradation rate (Gupta et al., 2025; Nasr et al., 2019).

Effect of other compounds

Wastewater samples commonly contain both organic and inorganic pollutants. Therefore, the influence of other pollutants on CFA degradation efficiency was investigated. As shown in Fig. 5, the coexistence of inorganic ions such as Na^+ and Cl^- does not influence the removal efficiency of CFA. However, in the presence of other organic compounds like TC

and OF, CFA degradation efficiency drops by about 5–8%. This reduction is likely due to these organics competing for catalyst sites, consuming reactive species ($\bullet\text{OH}$, $\text{O}_2\bullet^-$, h^+), and blocking light (Gupta et al., 2025; Li et al., 2018; Mayoufi et al., 2014; Sukhadeve & Gedam, 2023; Sukhadeve et al., 2023).

Reuse of Cu-TiO_2 photocatalyst

Figure 6 presents the reusability of Cu-TiO_2 and the amount of Cu released after five cycles of CFA degradation. CFA removal efficiency decreased slightly in the first three cycles, with a 6.7% drop by the third cycle. However, the degradation efficiency of CFA remained high at 74.6% in the fifth run, indicating good reusability of the doped photocatalyst (Fig. 6a). The observed decline in CFA efficiency after five cycles may result from material loss during washing and recovery processes or from the accumulation of intermediates on the catalyst surface. Besides, the release of Cu ions after five cycles was less than 1.8% compared with the original photocatalyst (Fig. 6b). The low level of copper leaching indicates that Cu-TiO_2 is unlikely to cause secondary pollution (Kim & Lee, 2018).

Fig. 5 Effect of other compounds on CFA removal using TiO_2 and Cu-TiO_2

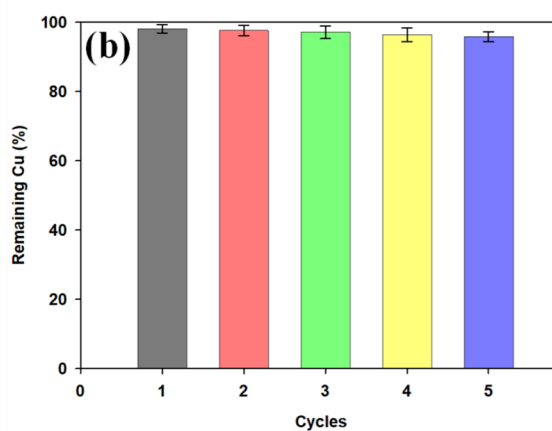
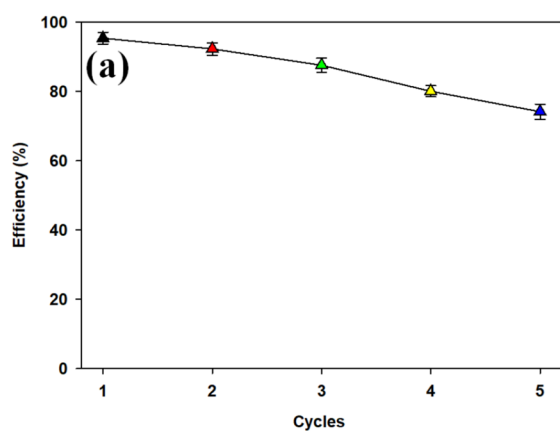
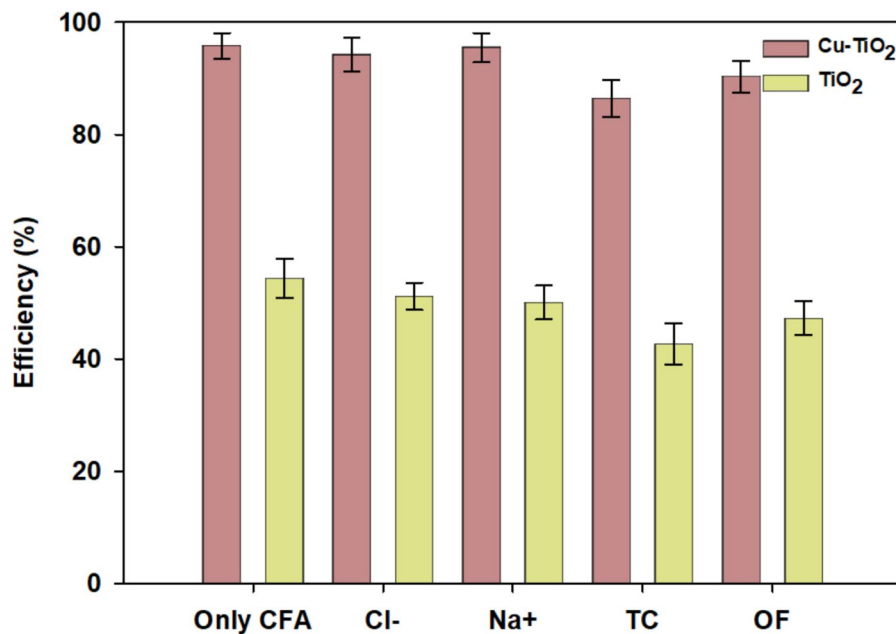


Fig. 6 Reusability of Cu-TiO_2 (a) and Cu remaining in the reused catalyst (b)

Effect of solution pH

Typically, each type of wastewater has its own pH value, depending on the sources of pollutants and other characteristics. Hence, the effect of solution pH on the removal of CFA using TiO_2 and Cu-TiO_2 was investigated (Text S3, Fig. S4).

Reduction of total organic carbon

Figure 7a shows that after 90 min of reaction time, the reduction of TOC using TiO_2 and Cu-TiO_2 was 51.8% and 98.2%, respectively. This means that during the photodegradation process, CFA was broken down into simpler, non-organic materials (Hamid &

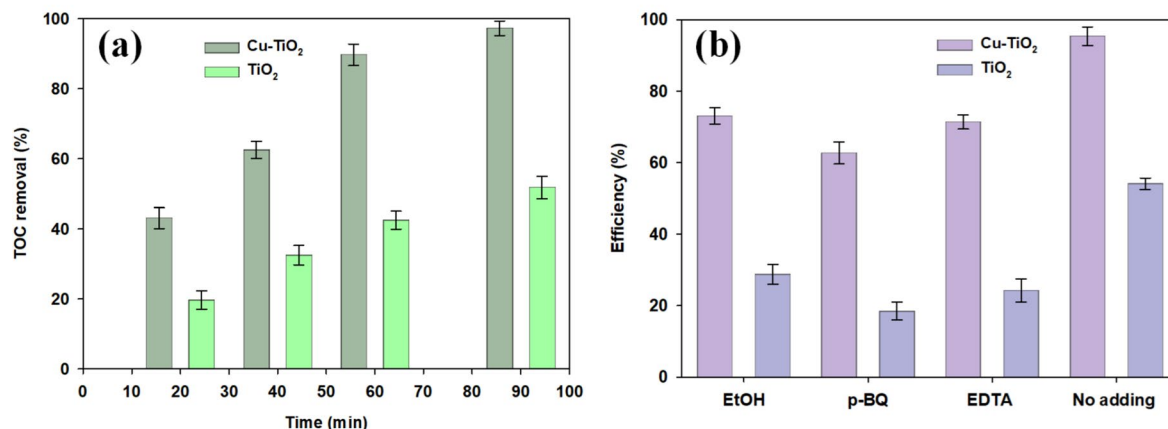


Fig. 7 TOC removal **a** and radical quenching **b** during degradation of CFA

Khanday, 2026; Jang et al., 2025; Jitae et al., 2025). Figure 7b presents the impact of radical scavengers on the degradation of CFA using TiO₂ and Cu-TiO₂ photocatalysts. The results show that the addition of EtOH, EDTA, and p-BQ rapidly reduced the degradation efficiency of CFA from 95.6% to 73.1%, 70.9%, and 62.6%, respectively. Therefore, hydroxyl radicals, superoxide radicals, and holes play important roles in the degradation of the CFA pollutant. However, superoxide radicals are more effective than holes and hydroxyl radicals. The findings are consistent with previous reports on the degradation of organic pollutants using TiO₂-based photocatalysts (Chung et al., 2016; Gan et al., 2022; Gupta et al., 2025; Mayoufi et al., 2014; Piątkowska et al., 2023; Zhang et al., 2018).

Intermediate products analysis

LC-MS analysis was used to identify degradation intermediates of CFA. The obtained *m/z* values and tentative molecular formulas of the by-products are listed in Table S1.

The results reveal that during the photodegradation process, CFA decomposes into intermediate products, including CFA-1 (*m/z* = 263.1), CFA-2 (*m/z* = 315), CFA-3 (*m/z* = 206.09), CFA-4 (*m/z* = 274), CFA-5 (*m/z* = 239.1), and CFA-6 (*m/z* = 191.2). The degradation of CFA using the Cu-TiO₂ photocatalyst occurs through interactions with radicals such as •OH and O₂•⁻, as confirmed

in previous studies (Gupta et al., 2025; Jiménez-Salcedo et al., 2020; Khan et al., 2024; Lima et al., 2020). Moreover, the TOC results corroborate that, in the presence of Cu-TiO₂ and solar light, CFA was degraded and mineralized into CO₂, H₂O, and inorganic ions.

Degradation mechanism of CFA

Based on the above results, the degradation mechanism of CFA using Cu-TiO₂ under solar light is proposed, as shown in Fig. 8.

The degradation of CFA using Cu-TiO₂ is proposed based on previous work on metal-doped TiO₂ photocatalysts (Gupta et al., 2025; Kim & Lee, 2018; Li et al., 2018; Mayoufi et al., 2014; Sukhadeve & Gedam, 2023; Sukhadeve et al., 2023). Under light, electrons in the valence band (VB) of TiO₂ are excited to the conduction band (CB), leaving holes (h⁺). After moving to the CB, electrons can be captured by Cu²⁺ ions, thereby inhibiting e⁻/h⁺ recombination. Consequently, the electrons readily reduce dissolved O₂ to superoxide radicals (O₂•⁻), while the holes oxidize H₂O to produce hydroxyl radicals (•OH). As strong oxidants, O₂•⁻ and •OH attack the CFA molecules, cleaving functional groups to form smaller, simpler by-products that continue to degrade and ultimately mineralize to inorganic species (e.g., CO₂ and H₂O).

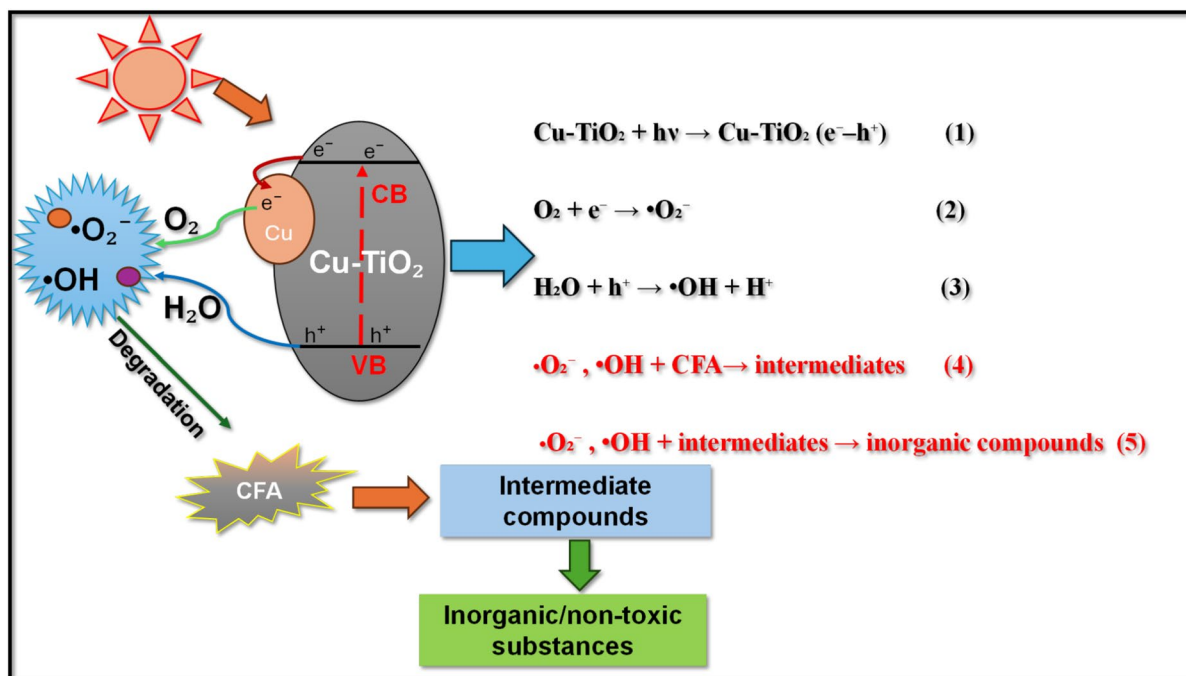
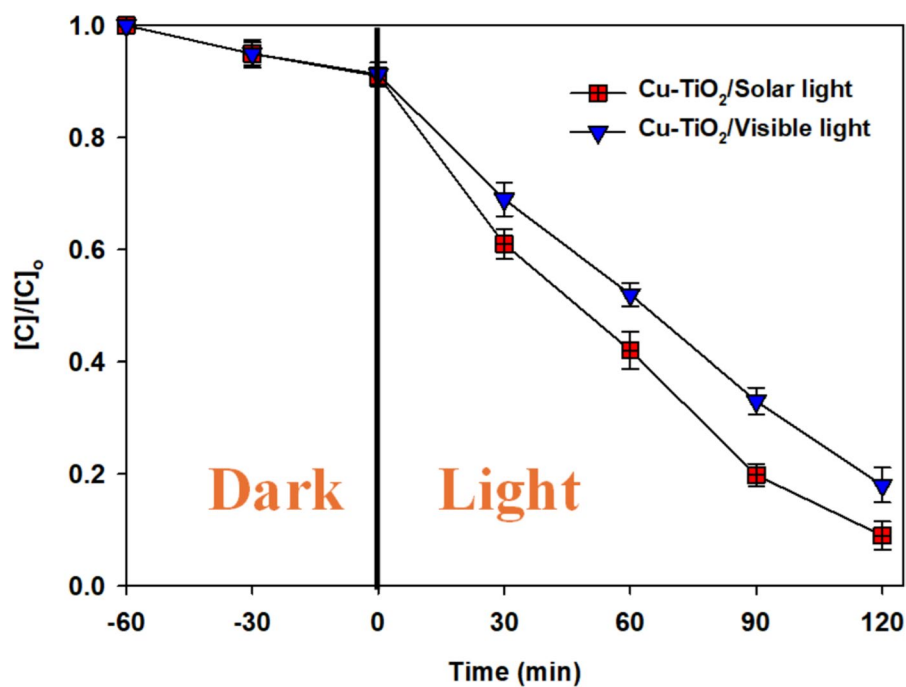


Fig. 8 Degradation mechanism of CFA using Cu-TiO₂ photocatalyst

Fig. 9 Removal of CFA from wastewater using Cu-TiO₂



Removal of CFA from wastewater

To evaluate the practical applicability of Cu–TiO₂, the photocatalyst was tested with wastewater sample (Text S4). Figure 9 presents the CFA removal efficiency using Cu–TiO₂ in the dark and under different light sources. The result clearly showed that in the absence of light, the removal performance of CFA was less than 10%, suggesting that the adsorption process driven by Cu–TiO₂ is limited (Gan et al., 2022; Hickman et al., 2018; Liang et al., 2024). However, when exposed to light, Cu–TiO₂ exhibits remarkable performance in oxidizing CFA, with removal rates of 94.1% under solar light and 85.7% under visible light. The findings further confirm the role of the light source, and with its high removal efficiency of CFA from wastewater, Cu–TiO₂ is a promising candidate for the treatment of wastewater generated by hospitals, healthcare facilities, and the pharmaceutical industry (Ahmad et al., 2024; Khan & Shah, 2023).

Evaluation of using Cu–TiO₂ for removal of CFA antibiotic residues

Cost-effective and potential scale-up

Table 3 presents the removal efficiencies of CFA using various materials and operating conditions. It displays that advanced oxidation process approaches, including ozonation (90%) and catalytic wet-air oxidation (95%), brought high efficiency but require substantial energy or chemical input. Besides, adsorption using GO/chitosan (78.17%) and CSN@GO (67.6%) showed lower removal performance and only transferred contaminants from the liquid phase to the solid phase, without mineralization (Duong et al., 2025; Vamsi et al., 2024). Among photocatalysts, undoped TiO₂ exhibits high efficiency under UV irradiation (88.3%), while dye-sensitized TiO₂ hits around 75% under visible light. Doped catalysts, such as Au–TiO₂ (91%) and Fe–N–TiO₂ (71%), also exhibit good removal performance of CFA under different light

Table 3 Removal performance of CFA using different materials/methods

Material	Method	Efficiency/ condition	References
Ce-based UiO-66	Adsorption, photocatalysis	96%/ UV light	Kusworo et al., (2025)
Ozone	Ozonation	90%/ Ozone	Oliveira et al., (2024)
Functionalized carbon nano-tube/ Ozonation	Adsorption + AOPs	70%/ ozone	Oliveira et al., (2024)
CeO ₂ / ZnO	Photocatalysis	60%/ UV light	Wolski et al., (2021)
ZnO		38%/ UV light	Wolski et al., (2021)
FeSAC	Catalyst wet air oxidation	95%/ 120 °C/ 20 bar	Gutiérrez-Sánchez et al., (2023)
GO/chitosan beads	Adsorption	78.17%	Duong et al., (2025)
CSN@GO	Adsorption	67.6%	Vamsi et al., (2024)
CdS/UiO-66 MOF	Photocatalysis	94%/ Visible light	Wu et al., (2025)
Fe-ZIF-8@AgCl	Photocatalysis	71.9%, Solar light	Liang et al., (2025)
MIF/BOI	Fenton-like, piezo Photocatalysis	95%/ Visible	Jabbar et al., (2025)
PS-TiO ₂	Photocatalysis	95.01% /Visible	Hayri-Senel et al., (2024)
Au-TiO ₂	Photocatalysis	91%/ UV light	Martins et al., (2020)
Au-TiO ₂	Photocatalysis	49%/ Visible light	Martins et al., (2020)
TiO ₂ /glass plate	Photocatalysis	92.81/ UV-C	Malakootian et al., (2020)
Fe–N–TiO ₂	Photocatalysis	71%/ LED light	Suwannaruang et al., (2020)
PM-TiO ₂ -Pd	Sono-photocatalysis	79.44%/ LED lamp	Motlagh et al., (2021)
HC + UV + P-TiO ₂	Photocatalysis	90.63%/Solar light	Chen et al., (2023)
TiO ₂	Photocatalysis	88.3%/ UV	Parmar and Srivastava, (2022)
Dye sensitization of TiO ₂	Photocatalysis	75%/ Visible	Krishnan and Shrivastav, (2023)
Cu-TiO ₂	Photocatalysis	94.1%/ Solar light	This work
Cu-TiO ₂	Photocatalysis	85.7%/ Visible light	This work

conditions (Krishnan & Shriwastav, 2023; Martins et al., 2020; Parmar & Srivastava, 2022; Suwannarung et al., 2020). Moreover, combined methods or materials exhibit excellent removal performance of antibiotic pollutants. For example, the removal efficiencies of CFA using PS-TiO₂, CdS UiO-66 MOF, MIF/BOI, and Ce-based UiO-66 were 95.01%, 94%, 95%, and 96%, respectively (Ali et al., 2024; Hayri-Senel et al., 2024). In this work, Cu-TiO₂ removed 94.1% and 85.7% of CFA from wastewater under solar and visible light, respectively. On the other hand, it does not require elevated temperature, pressure, or additional chemicals/reagents, distinguishing it from other high-performing methods. Therefore, Cu-TiO₂ is a promising candidate for practical applications to remove antibiotic residues from wastewater. In addition, compared with other advanced oxidation routes that require heat, pressure, or added chemicals/reagents, Cu-TiO₂ offers a low-cost, visible-light-driven approach that exploits natural sunlight (Farkas et al., 2024; Jabbar et al., 2025; Mojiri et al., 2019; Zhang et al., 2024a, 2024b). Besides, TiO₂ itself is already mass-produced and inexpensive, and Cu is a common and low-cost metal (Domínguez-Espíndola et al., 2022; Khan & Shah, 2023). The Cu-doping process is simple and can be relatively easily scaled up to produce large amounts of photocatalyst. In this study, Cu-TiO₂ exhibits high degradation efficiency for CFA in wastewater (>94%) under solar irradiation, while maintaining good reusability over multiple cycles. Moreover, catalyst loss and Cu-ion release are low, reducing operating costs associated with replacement and secondary pollution control.

Reduce potential risks of antibiotic residues

Unlike adsorption, which only transfers pollutants to the adsorbent surface, with the risk of desorption and secondary handling, photocatalysis can mineralize antibiotic pollutants into harmless end products (CO₂, H₂O, and inorganic ions), as indicated by total organic carbon reduction (Chen et al., 2023; Hayri-Senel et al., 2024; Krishnan & Shriwastav, 2023; Martins et al., 2020; Parmar & Srivastava, 2022). Cu-TiO₂ can remove more than 94% of CFA from wastewater, which helps lower antibiotic residues and limits the spread of resistant bacteria in water. Reducing antibiotic-resistant bacteria improves public health, eases pressure on healthcare systems, and

lessens economic challenges, especially in developing countries (Cocker et al., 2025; Mishra et al., 2026; Savin et al., 2021). Poor regulation of drug sales and ineffective wastewater treatment have allowed large amounts of antibiotics to enter the environment, mainly through water sources. These antibiotic residues are persistent and difficult to break down, persistently affecting ecosystems and promoting the growth of bacteria with resistance genes (Yang et al., 2023; Zhai et al., 2024; Zhang et al., 2023). Such bacteria are hard to control because they spread quickly and pose health risks that are not yet fully understood (Bonetta et al., 2023; Savin et al., 2021). Therefore, applying an effective method, such as Cu-TiO₂/solar light, to remove antibiotic residues in wastewater could bring various environmental benefits and enhance public health.

Limitation remains

Despite these advantages, Cu-TiO₂ exists in powder form and can be partially lost during reuse and recovery. Thus, loading Cu-TiO₂ onto durable supports (glass, ceramic foams, stainless-steel meshes, carbon cloth, or polymer membranes) or using magnetically retrievable hybrids can reduce catalyst separation costs and losses (Ahmad et al., 2024; Khan & Shah, 2023). Despite these advantages, Cu-TiO₂ exists in powder form and can be partially lost during reuse and recovery. Thus, loading Cu-TiO₂ onto durable supports (glass, ceramic foams, stainless-steel meshes, carbon cloth, or polymer membranes) or using magnetically retrievable hybrids can reduce catalyst separation costs and losses (Tanji et al., 2023; Thakur et al., 2024). Besides, as a metal-oxide catalyst, Cu-TiO₂ exhibits limitations in low pH wastewater. The application of protective coatings with other materials may enhance the suitability for use in a wide range of wastewater types. In addition, the simultaneous removal of coexisting antibiotics and other micropollutants, as well as tests with wastewater in different seasons, should be conducted (Ahmad et al., 2024; Khan & Shah, 2023).

Conclusions

This study evaluates an effective method for removing antibiotic residues from wastewater using

Cu-doped TiO₂ photocatalyst. The synthesized catalyst showed good optical properties, with high visible-light absorption and narrowed band-gap energy (2.7 eV). Cu–TiO₂ effectively removed 94.1% of CFA from wastewater, which is higher than that of other materials. According to the Langmuir–Hinshelwood kinetic model, Cu–TiO₂ required less reaction time (14.7 min) to degrade 50% of CFA than TiO₂ (69.3 min). Moreover, it maintained high photodegradation performance after five reuse cycles. In addition, this work highlighted the cost-effectiveness, scalability, and environmental benefits of using the Cu–TiO₂ photocatalyst to control antibiotic residues in wastewater.

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