

CeO₂-CuO nanoparticles modified bamboo charcoal for antibiotic degradation: Photocatalysis enhanced peroxymonosulfate activation

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Research Article

Keywords: Bamboo charcoal, cerium dioxide, cupric oxide, tetracycline degradation

Posted Date: July 3rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10126332/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Water, Air, & Soil Pollution on September 9th, 2026. See the published version at <https://doi.org/10.1007/s11270-026-09924-0>.

Abstract

Bamboo charcoal, with its porous structure and abundant surface functional groups, serves as an ideal carrier for loading nano-catalysts. This study used bamboo powder as carrier material and achieved the complexation of copper and cerium ions with citric acid through a solvothermal reaction in an alkaline CH_3OH -DMF solution, leading to the preparation of $\text{Cu}^{2+}/\text{Ce}^{3+}$ -modified bamboo powder. Subsequently, CeO_2 -CuO nanoparticles doped bamboo charcoal (Cu/Ce-BC) was prepared by pyrolyzing the modified bamboo powder at 500°C . Structural and morphological characterization revealed that the generated CeO_2 and CuO nanoparticles were loaded on the surface of bamboo charcoal, providing abundant active sites for the catalytic activation of peroxymonosulfate (PMS). Under visible-light irradiation, the Cu/Ce-BC/PMS system can degrade 90.6% of tetracycline (TC) within 70 min. Furthermore, experiments involving radical scavengers verified that both $\text{SO}_4^{\cdot-}$ and $\cdot\text{OH}$ were produced in the reaction solution. Mechanistically, the bimetal redox cycle based on $\text{Cu(I)}/\text{Cu(II)}-\text{Ce(III)}/\text{Ce(IV)}$ can effectively activate PMS, and the electrons are transferred from Cu(I) to Ce(IV) in the redox reaction to establish a synergistic redox cycle, achieving the sustained generation of Ce(III). With CeO_2 and CuO as photocatalytic active sites, visible-light-induced electron transfer activated PMS into $\text{SO}_4^{\cdot-}$ and $\cdot\text{OH}$ radicals, which subsequently oxidized and degraded TC. The design and synthesis of CeO_2 -CuO doped bamboo charcoal catalysts provide a green technological solution for the treatment of antibiotic pollution.

1. Introduction

At present, antibiotics, serving as an essential category of pharmaceuticals employed to counteract microbial infections, have found extensive utilization across a broad spectrum of domains, encompassing both therapeutic medicine and livestock husbandry (Terreni et al. 2021). Nevertheless, the widespread application of antibiotics has precipitated an environmental concern: the pervasive contamination of our ecosystems by these pharmaceutical compounds. Antibiotic pollution in water bodies and soil triggers a chain reaction in the ecosystem, ultimately posing risks to human health. Antibiotics have become a major challenge for wastewater treatment due to their structural stability and resistance to degradation (Padmanabhan et al. 2025). For example, tetracycline residues are frequently detected in aquatic environments (Singh et al. 2025). Hence, the enhancement of regulatory oversight of antibiotic contamination in the environment has emerged as a pivotal global imperative.

Cerium oxide (CeO_2) is a n-type semiconductor with a wide band gap of 2.6–3.4 eV (Murugadoss et al. 2021). CeO_2 based heterogeneous photocatalysts are commonly used for the degradation of organic compounds under visible light. For instance, Aoun et al. prepared a SrNiO_3 perovskite/ CeO_2 composite, which could be used for the photocatalytic oxidation of 2-propanol under solar light (Aoun et al. 2025). Both CuO and CeO_2 are suitable for photocatalytic purposes (Luo et al. 2024). Nevertheless, neither of them alone can achieve high visible-light photocatalytic activity in practical applications, primarily due to their rapid electron–hole recombination (Garcia-Lopez et al. 2021). The construction of CuO/ CeO_2 composites can enhance the photocatalytic activity by forming more oxygen vacancies. Sun et al.

reported a CuO/CeO₂ composite catalyst for the selective catalytic oxidation of ammonia. Biochar-supported catalysts are a type of heterogeneous catalyst in which active metals or metal oxides are dispersed on a biochar carrier (Sun et al. 2023). Moreover, Copper-based catalysts showed effective activity in PMS activation with diverse activation pathways (Chen et al. 2023b). For example, Zhu et al. identified ¹O₂ as the dominant reactive species in PMS activation mediated by a Cu-Cu₂O-CuO loaded carbon catalyst (Zhu et al. 2024). Biochar, with its porous structure and abundant surface functional groups, serves as an ideal antibiotic adsorbent and nano-catalysts carrier (Xu et al. 2026). Researches have shown that the adsorption of both PMS and antibiotic compounds onto biochar facilitates PMS activation and subsequently enhances antibiotic degradation (Ma et al. 2025). Zhang et al. prepared the CuS@Fe-CCBC catalyst by loading CuS and Fe active sites onto corn core biochar, which can activate more than 99.2% of peroxymonosulfate (PMS) for rapid degradation of sulfonamide antibiotics (Zhang et al. 2025). Moreover, the spatially confined integration of photocatalytic and Fenton-active sites within a single heterogeneous catalyst facilitates synergistic pollutant degradation through accelerated interfacial electron transfer and sustained in situ generation of reactive oxygen species (ROS). Tian et al. incorporated g-C₃N₄ quantum dots into mesoporous CuO-SiO₂ to synthesize a catalyst. In the catalyst, g-C₃N₄ served as a photogenerated electron separation center, transferring electrons to CuO to accelerate the conversion efficiency of Cu²⁺/Cu⁺, promoting the generation of active species (Tian et al. 2021).

In this study, natural bamboo powder was used as the raw material to prepare biochar catalyst. Under hydrothermal conditions, citric acid was employed to complex Cu²⁺ and Ce³⁺ on the surface of the bamboo powder. Subsequently, the bamboo charcoal catalyst loaded with CuO and CeO₂ (Cu/Ce-BC) was prepared through pyrolysis at 500°C. Cu/Ce-BC can efficiently degrade tetracycline (TC) under the assistance of visible light. The Cu/Ce-BC catalyst can activate PMS under visible light assistance to degrade tetracycline with high efficiency. Mechanism study showed that, the bimetal redox cycle based on Cu⁺/Cu²⁺–Ce³⁺/Ce⁴⁺ can effectively prevent the deactivation of active sites and continuously generate highly active SO₄^{•−} and ·OH.

2. Experimental

2.1. Materials and reagents

The bamboo material used in the experiment was *Phyllostachys edulis*, which was collected from rural areas of Lincang, Yunnan Province, and processed into 200-mesh bamboo powder after being crushed for later use. Citric acid (99.5%), Ce(NO₃)₃·6H₂O (99%), Cu(NO₃)₂·3H₂O (99%), potassium peroxymonosulfate (PMS, KHSO₅ > 40%), and tetracycline hydrochloride (TC, 98%) were purchased from Titan Scientific Co., Ltd.

2.2. Preparation method

Firstly, 2.0 g of bamboo powder was added to a flask, followed by 15 mL of an alkaline methanol-DMF solution, and the mixture was refluxed at 60°C for 60 min to obtain alkali-activated bamboo powder. To

the above mixture, citric acid (3 mmol) was added, and after stirring for 30 min, $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (3 mmol) and $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ (3 mmol) were added, followed by continued stirring for another 30 min. Transfer the mixture into a 100 mL PTFE-lined autoclave and heat it at 120°C for 12 h to allow the reaction to proceed. The filtered powder was dried in an oven at 50°C to obtain copper-cerium-loaded bamboo powder (Cu/Ce-BP). The modified bamboo powder was placed in a tube furnace and carbonized by heating at 500°C for 3 h under a nitrogen atmosphere, with a heating rate of 5°C/min. The obtained bamboo charcoal catalyst was designated as Cu/Ce-BC. The synthetic route of Cu/Ce-BC is shown in Fig. 1.

2.3. Instruments and characterizations

The XPS spectra of the Cu/Ce-BC catalyst were obtained using a Thermo Scientific K-Alpha X-ray photoelectron spectrometer with an Al K α source. The infrared spectroscopy (FTIR) was tested by a Bruker tensor 27 spectrometer, Germany. The powder X-ray diffraction data was observed by a Rigaku Ultima IV X-ray diffractometer, Japan, with the X-ray source being Cu K α (0.15406 nm). The morphology of the catalyst was observed by a ZEISS Sigma 300 scanning electron microscopy, Germany. Bamboo charcoal is produced by calcining in a tube furnace (Kecheng, Hefei).

2.4. Photocatalytic degradation experiments

This study aims to use a 20 mg/L tetracycline (TC) solution as the target pollutant to investigate the degradation efficiency of tetracycline in the Cu/Ce-BC/PMS system. Firstly, 40 mg of the Cu/Ce-BC catalyst was added to 50 mL of a tetracycline solution in a reaction beaker and stirred in the dark for 30 min to achieve adsorption equilibrium. Then, 0.1 mmol of PMS ($\text{KHSO}_5 > 40\%$) was added into the solution as an oxidant, with a xenon lamp (300 W) serving as the light source. Subsequently, 2.5 mL of the solution was sampled every 20 min, and the absorbance of TC was measured using a UV-Vis spectrophotometer to calculate its degradation efficiency. Moreover, the effects of PMS dosage, initial pH, and free radical scavengers on the degradation efficiency of TC were also investigated. The degradation efficiency of TC at different reaction times was calculated according to the following formula (Wang et al. 2026a).

$$\text{Degradation efficiency} = (C_0 - C_t) / C_0 \times 100\% \quad (1)$$

3. Results and discussion

3.1. Structural and morphology characterizations

From the XRD pattern (Fig. 2a), it can be observed that the Cu/Ce-BC sample exhibits diffraction peaks at $2\theta = 35.38^\circ$, 38.57° , and 48.79° , which correspond to the characteristic peaks of CuO (PDF#97-008-7123). By comparison with the standard PDF card of CeO_2 (PDF#97-018-2988), it can be determined that the diffraction peaks appearing at 28.54° , 47.48° , and 59.09° are the characteristic peaks of CeO_2 (Ma et

al. 2024). The diffraction peaks of the CuO phase in the Cu/Ce-BC sample are narrow and sharp, indicating well-crystallized crystals with high crystallinity. The broad diffraction peaks of CeO₂ phase indicate that it has a small crystallite size(Ameen 2025).

In the infrared (IR) spectrum of Cu/Ce-BC (Fig. 2b), the absorption peaks located at 3400 cm⁻¹ and 1680 cm⁻¹ are the vibration absorption peaks of O-H and C = O, respectively, indicating there are a large number of carboxyl groups (-COOH) on the surface of the biochar. Distinct aromatic ring absorption peaks are found at the position centered at 1400 cm⁻¹, which can be attributed to the formation of graphite structure in the biochar. Furthermore, strong M-O absorption peaks of metal oxides are observed at about 500 cm⁻¹, indicating the presence of CuO and CeO₂. The weight loss behavior of the modified bamboo powder during calcination was analyzed through thermogravimetric testing. Figure 2c presents the TG-DTG curves of the modified bamboo powder (BP), revealing a pronounced mass loss within the temperature range of approximately 200–400°C. This sharp decline in mass indicates the occurrence of thermal decomposition in the modified bamboo powder as the temperature increases. This is the crucial stage where the internal substances of the bamboo charcoal are reconstructed to form CuO, CeO₂, and graphite carbon. Beyond 400°C, the mass of the sample exhibited a gradual decline, signifying that thermal decomposition or oxidation processes continued to proceed at elevated temperatures. From the TG curve, it is evident that when the temperature rises to 500°C, the remaining mass of the bamboo charcoal composite is 39%.

The morphology and surface elemental distribution of Cu/Ce-BC were characterized using scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS). SEM images (Fig. 2d-g) show that the surface of bamboo charcoal is loaded with a layer of nanoparticles, which are mainly composed of CeO₂ and CuO nano-crystals. Figure 2f–g reveals that the crystalline nanoparticles exhibit a uniform size distribution ranging from 10 to 100 nm and are stably anchored onto the bamboo charcoal surface. EDS elemental mappings (Fig. 2h–l) reveal homogeneous spatial distribution of Cu, Ce, and O elements across the Cu/Ce-BC surface, providing direct evidence for the in-situ formation of CeO₂ and CuO nanoparticles on the bamboo charcoal matrix during pyrolysis of the modified precursor at 500°C. Microstructurally, the Cu/Ce-BC surface features a rich distribution of nanoscale active sites that enhance both light-energy absorption and peroxymonosulfate (PMS) activation, thereby enabling efficient tetracycline (TC) degradation.

3.2. X-ray photoelectron spectroscopy

The chemical states and composition of the bamboo charcoal (Cu/Ce-BC) were analyzed using X-ray photoelectron spectroscopy (XPS)(Niaz et al. 2023). From the XPS survey spectrum (Fig. 3a), characteristic binding energy peaks of C 1s, O 1s, Cu 2p, and Ce 3d can be clearly observed, confirming the coexistence of carbon, oxygen, copper, and cerium elements on the surface of the bamboo charcoal. In the high-resolution O 1s spectrum (Fig. 3b), the peak located at 532.08 eV can be attributed to lattice oxygen species, while the peak at 533.58 eV corresponds to the hydroxyl (-OH) functional groups on the

bamboo charcoal surface. In the C 1s spectrum (Fig. 3c), the peaks located at 284.80, 286.69, and 288.49 eV are attributed to C = C, C–O, and C = O bonds, respectively. The presence of these characteristic binding energy peaks indicates the existence of the graphite carbon and the surface carboxyl groups (–COOH)(Jeon et al. 2013). In the Cu 2p spectrum (Fig. 3d), the presence of the Cu 2p_{3/2} peak at 934.58 eV, the Cu 2p_{1/2} peak at 954.08 eV, and the satellite peaks indicates that copper primarily exists in the Cu(II) state. Additionally, the peaks observed at 932.38 eV and 952.22 eV suggest the presence of a small amount of copper in lower oxidation states. The high-resolution spectrum of the Ce element exhibits complex Ce 3d_{5/2} and Ce 3d_{3/2} binding energy peaks (Fig. 3e). Figure 3f displays the mass-based elemental distribution of Cu/Ce-BC, indicating that carbon constitutes the predominant element by weight.

3.3. Evaluation of catalytic activity

As shown in Fig. 4a, the intensity of the UV-Vis absorption spectrum of tetracycline (TC) in the Cu/Ce-BC/PMS (0.1 mmol) system gradually decreased with the extension of reaction time under visible-light irradiation, indicating that TC could be rapidly degraded under this system. In the later stage of the reaction, as the concentrations of the TC and PMS continuously decreased, and the competitive adsorption of degradation intermediates on the active sites of the catalyst, the degradation rate of TC decreased significantly. The degradation efficiency of TC reached 90.6% after 70 min of reaction under visible-light irradiation, whereas it was only 72.8% in the dark (Cu/Ce-BC dark control) (Fig. 4b), indicating a notable photocatalytic contribution to the overall degradation process. Moreover, the catalytic performance of Cu/Ce-BC significantly surpassed that of the individual metal oxides CuO (36.5%) and CeO₂ (16.8%) (Fig. 4b). Our experiments demonstrated that increasing the dosage of PMS has a very limited effect on the degradation efficiency of TC, and when increasing the dosage of PMS to 0.5 mmol even leads to a slight decrease in the degradation efficiency (Fig. 4c). This is attributed to excessive PMS causing partial scavenging of the reactive oxygen species (ROS), thereby suppressing TC degradation. As shown in Fig. 4d, the linear fitting results of the data indicate that the degradation process of TC in the Cu/Ce-BC/PMS system conforms to the pseudo-first-order reaction kinetics. For example, when the dose of PMS was 0.1 mmol, the apparent rate constant k was 0.0272 min^{−1}.

The influence of pH on the degradation efficiency of TC was studied by altering the initial pH of the solution. As depicted in Fig. 4e, Cu/Ce-BC exhibits excellent catalytic efficiency within the pH range of 2 to 8, indicating that the catalyst has good pH adaptability. The experimental results show that the optimal pH range for Cu/Ce-BC/PMS system is 6 to 8. In the reuse experiments, we found that Cu/Ce-BC has stable cycling performance in the degradation of TC. When the catalyst was recycled for 4 times, the degradation efficiency of TC still remained at 85.3%. The immobilization of metal oxide (MO_x) active sites onto biochar supports for advanced oxidation processes (AOPs)-mediated pollutant degradation exhibits multiple distinct advantages, including enhanced catalytic stability, improved electron transfer efficiency, and significantly enhanced the adsorption efficiency of PMS and TC (Xue et al. 2025). Besides, loading CuO and CeO₂ onto the surface of biochar can reduce the metal leaching during the degradation

process of pollutants. After 70 min of catalytic reaction, the concentrations of Cu^{2+} and Ce^{4+} in the solution were detected to be 0.032 mg/L and 0.015 mg/L respectively, indicating that the leaching of metal ions was controlled at a relatively low level.

3.4. Electrochemical analysis and quenching experiment

The electrochemical performance of Cu/Ce-BC was tested using a three-electrode system, and the working electrode was prepared by immobilizing the Cu/Ce-BC powders on nickel foam. The electrodes are immersed in a 0.05 mol/L sodium sulfate solution. Figure 5a shows the cyclic voltammetry (CV) curves of the Cu/Ce-BC catalyst at different scan rates. The cyclic voltammetry curve shows distinct oxidation and reduction peaks, indicating that the catalyst has good redox properties. At a scan rate of 0.4 mV/s, the CV curve exhibits the largest enclosed area, indicating excellent charge transport performance and effective interface reactions. As shown in Fig. 5b, Cu/Ce-BC exhibited a measurable photocurrent under visible-light irradiation. This confirms that CuO and CeO_2 on the catalyst surface absorb photons, inducing electron transitions and generating photogenerated charge carriers. In the electrochemical impedance spectroscopy (EIS) Nyquist plot of Cu/Ce-BC (Fig. 5c), the curve exhibits a straight-line trend with no obvious semicircular feature, suggesting low charge transfer resistance and favorable conductivity of the catalyst, which facilitates efficient separation of photogenerated electrons.

The trapping experiments were conducted under visible light to detect the reactive oxygen species generated in the Cu/Ce-BC/PMS system. In the experiments, tertiary butanol (TBA), methanol (MeOH), benzoquinone (BQ), and ethylene diamine tetraacetic acid (EDTA) were adopted as trapping agents, respectively. As displayed in Fig. 5d, the degradation of TC was effectively inhibited by TBA and CH_3OH , indicating $\cdot\text{OH}$ and $\text{SO}_4^{\cdot-}$ were the main oxidative active species in TC degradation process. The introduction of EDTA scavenger had a certain negative impact on the degradation efficiency of TC, indicating that holes (h^+) participated in the degradation of TC. In addition, the role of $\cdot\text{O}_2^-$ in the TC degradation process is very weak.

3.5. Density Functional Theory (DFT) calculations

The molecular electrostatic potential (ESP), molecular orbitals, and Fukui indices of tetracycline (TC) were calculated by DFT, and the main reaction sites of TC during the degradation process were further predicted. Two types of software, Gaussian 16 and Multiwfn(Lu 2024), were used in the calculation process. The optimized molecular configuration of TC is shown in Fig. 6a. In Fig. 6b, the blue areas represent positive electrostatic potential, and the red areas represent negative electrostatic potential. It is revealed that, the hydroxyl ($-\text{OH}$) and carbonyl ($\text{C}=\text{O}$) groups of the TC molecule exhibit negative electrostatic potential, whereas the methyl substituent displays a positive electrostatic potential. The ESP distribution provides a more detailed description of charge separation compared to the dipole moment, wherein regions of negative electrostatic potential are susceptible to electrophilic attack, while regions of positive electrostatic potential are prone to nucleophilic attack. The HOMO and LUMO orbital energies of TC are -5.74 eV and -1.94 eV (Fig. 6c and 6d), respectively, suggesting a high susceptibility

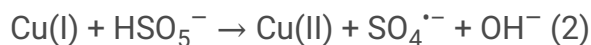
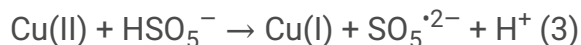
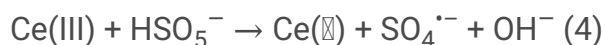
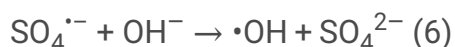
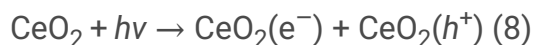
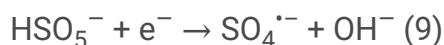
of TC to oxidation. The band gap (ΔE) = LUMO – HOMO = 3.8 eV, indicating TC has a low energy gap. The calculation results of Fukui indices show that the C₁₅ and O₂₂ site has a relatively high electrophilic Fukui index f^+ , indicating that these sites are more susceptible to attack by nucleophiles (Fig. 6e). The O₁₉ and O₂₀ sites have a relatively high neutral Fukui index f^0 , suggesting that they are more sensitive to free radical attacks.

3.6. Photo-Fenton catalytic mechanism

Based on electrochemical analysis, free radical quenching experiments, and DFT calculations, we proposed the photo-Fenton mechanism of Cu-Ce bimetallic synergistic activation of PMS. As illustrated in Fig. 6f, Cu/Ce-BC activates PMS via a synergistic redox cycle between Cu and Ce active sites, leading to the generation of reactive oxygen species (ROS) that drive the oxidative degradation of TC (Chen et al. 2023a). Initially, Cu(I) in the system react with PMS (HSO_5^-) via a redox process: Cu(I) is oxidized to Cu(II), concomitantly activating HSO_5^- to yield the sulfate radical ($\text{SO}_4^{\cdot-}$) and OH^- , as described in Eq. 2. Likewise, Ce(III) can also activate HSO_5^- to yield $\text{SO}_4^{\cdot-}$ and OH^- . In this process Ce(III) is oxidized to Ce(IV), thereby enhancing the generation of reactive oxygen species (Eq. 4). The generated high-valent Ce(IV) continue to obtain an electron from Cu(I), resulting in the reduction of Ce(IV) to Ce(III) and the oxidation of Cu(I) to Cu(II) (Eq. 5). The redox potential of Ce(IV)/Ce(III) ($E_0 = 1.44 \text{ V}$) is higher than that of Cu(II)/Cu(I) ($E_0 = 0.34 \text{ V}$), so electrons are transferred from Cu(I) to Ce(IV) in the redox reaction. This reaction established a synergistic redox cycle between Ce(III)/Ce(IV) and Cu(I)/Cu(II), achieving the regeneration of Ce(III). Subsequently, the generated $\text{SO}_4^{\cdot-}$ in the solution reacts with OH^- to produce more hydroxyl radicals ($\cdot\text{OH}$) (Eq. 6) (Yang et al. 2024).

As illustrated in Fig. 6g, the photocatalytic performance of CuO and CeO₂ also plays a critical role in PMS activation. The CuO and CeO₂ nanoparticles on the surface of bamboo charcoal undergo electron transition from the valence band to the conduction band under visible light irradiation (Uthirakumar et al. 2020), generating photogenerated electron(e^-)-hole(h^+) pairs (Eq. 7, 8) (Aoun et al. 2025). The PMS (HSO_5^-) adsorbed on Cu/Ce-BC captures one photogenerated electron, leading to the cleavage of the O–O bond and generating $\text{SO}_4^{\cdot-}$ and $\cdot\text{OH}$ radicals (Eq. 9). This process not only enhances the charge carrier separation efficiency but also produces highly oxidizing radical species. Additionally, water molecules in the solution are oxidized by the holes in the valence band of CeO₂, producing $\cdot\text{OH}$ radical and H^+ ion (Eq. 10). Finally, the photocatalytic process of CuO/CeO₂ synergistically cooperates with the redox cycle of Cu/Ce metal ions to activate PMS, generating a high concentration of $\text{SO}_4^{\cdot-}$ and $\cdot\text{OH}$ radicals, which oxidize and degrade TC in the solution. Recently, Wang et al. reported a photo-Fenton dual system based on MoS₂ and the Fe(III)/Fe(II) redox couple for phenol degradation (Wang et al. 2026b). From a mechanistic perspective, photogenerated electrons from MoS₂ continuously reduce Fe(III) to Fe(II), enabling sustained activation of PMS and subsequent generation of $\text{SO}_4^{\cdot-}$ and $\cdot\text{OH}$. Notably, Niu et al. reported the activation of persulfate (PS) by an Fe₂O₃/CeO₂ catalyst for tetracycline degradation,

attributing the sustained generation of $\text{SO}_4^{\bullet-}$ and $\cdot\text{OH}$ to synergistic redox cycling between Fe(III)/Fe(II) and Ce(IV)/Ce(III) couples (Niu et al. 2021). In our study, the reactions involved in the Cu/Ce-BC/PMS system are as follows:



4. Conclusion

In this study, a bamboo charcoal catalyst (Cu/Ce-BC) loaded with CuO and CeO_2 nanoparticles was prepared using natural bamboo powder as the raw material. The dual metal redox cycle of $\text{Cu}^+/\text{Cu}^{2+}$ and $\text{Ce}^{3+}/\text{Ce}^{4+}$ can synergistically activate peroxymonosulfate (PMS), and exhibits excellent degradation performance for tetracycline (TC). Cu/Ce-BC demonstrates good tetracycline (TC) degradation performance even at low PMS dosage (0.1 mM) and across a broad pH range. In particular, the bidirectional redox cycle based on $\text{Cu}^+/\text{Cu}^{2+}-\text{Ce}^{3+}/\text{Ce}^{4+}$ can effectively prevent the deactivation of active sites and continuously generate highly active $\cdot\text{SO}_4^-$ and $\cdot\text{OH}$. The rational design of bimetallic-modified biochar establishes a viable green catalytic platform for the Fenton-like degradation of emerging contaminants in wastewater.

CRedit authorship contribution statement

Jinchun Zhao: Investigation, Writing-original draft. **Fenghao Sun**: Formal analysis. **Biyong Feng**: Data curation. **Qipeng Li**: Methodology, Writing-review & editing. **Dawei Wang**: Conceptualization, Methodology, Writing-original draft.

Declarations

Conflict of Interest

There is no conflict of interest.

Author Contribution

Jinchun Zhao: Investigation, Writing-original draft. Fenghao Sun: Formal analysis. Biyong Feng: Data curation. Qipeng Li: Methodology, Writing-review & editing. Dawei Wang: Conceptualization, Methodology, Writing-original draft.

Acknowledgments

This work received financial support from the National Natural Science Foundation of China (32260427), and the Agricultural Basic Research Special Projects of Yunnan Province (202301BD070001-255).

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Figures

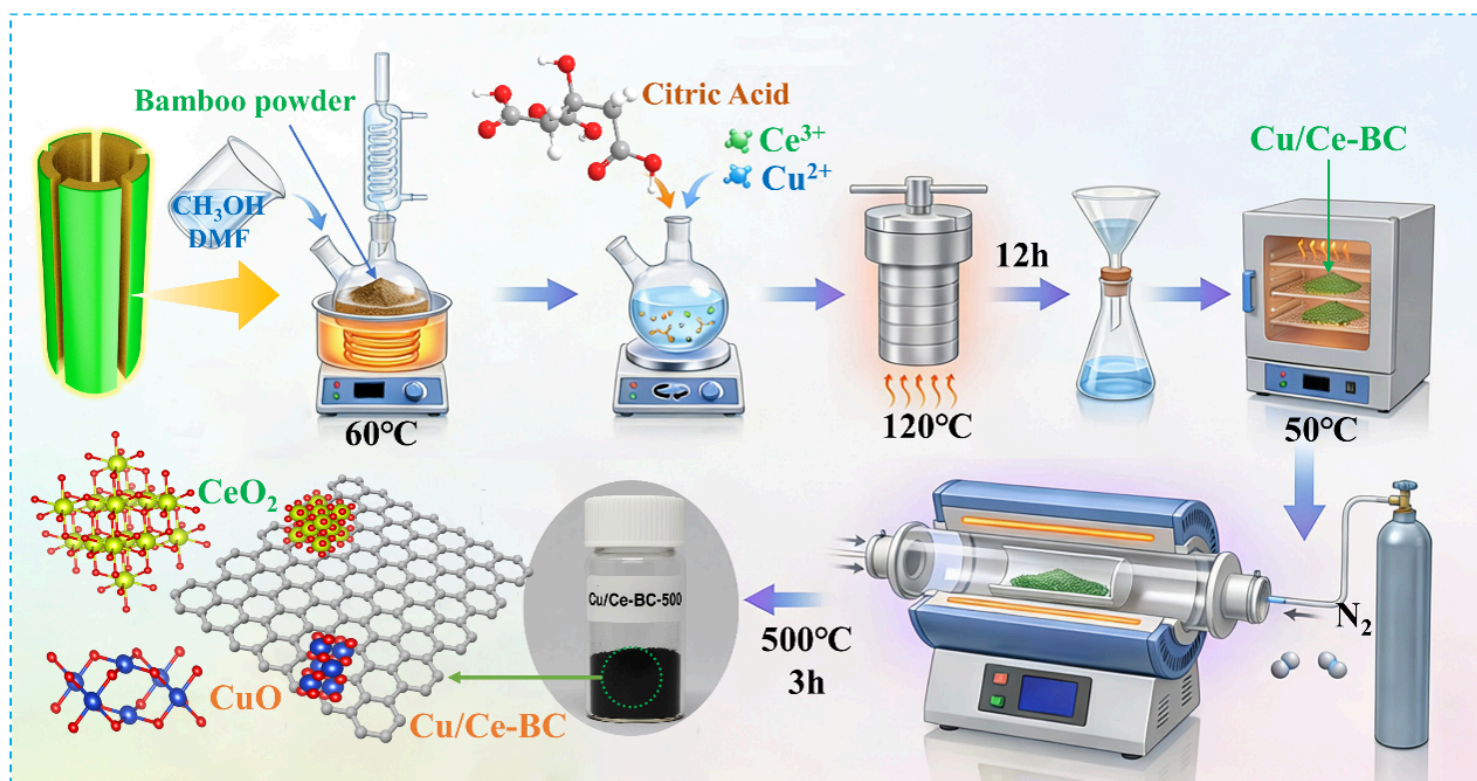


Figure 1

Schematic illustration of the preparation process of Cu/Ce-BC catalyst

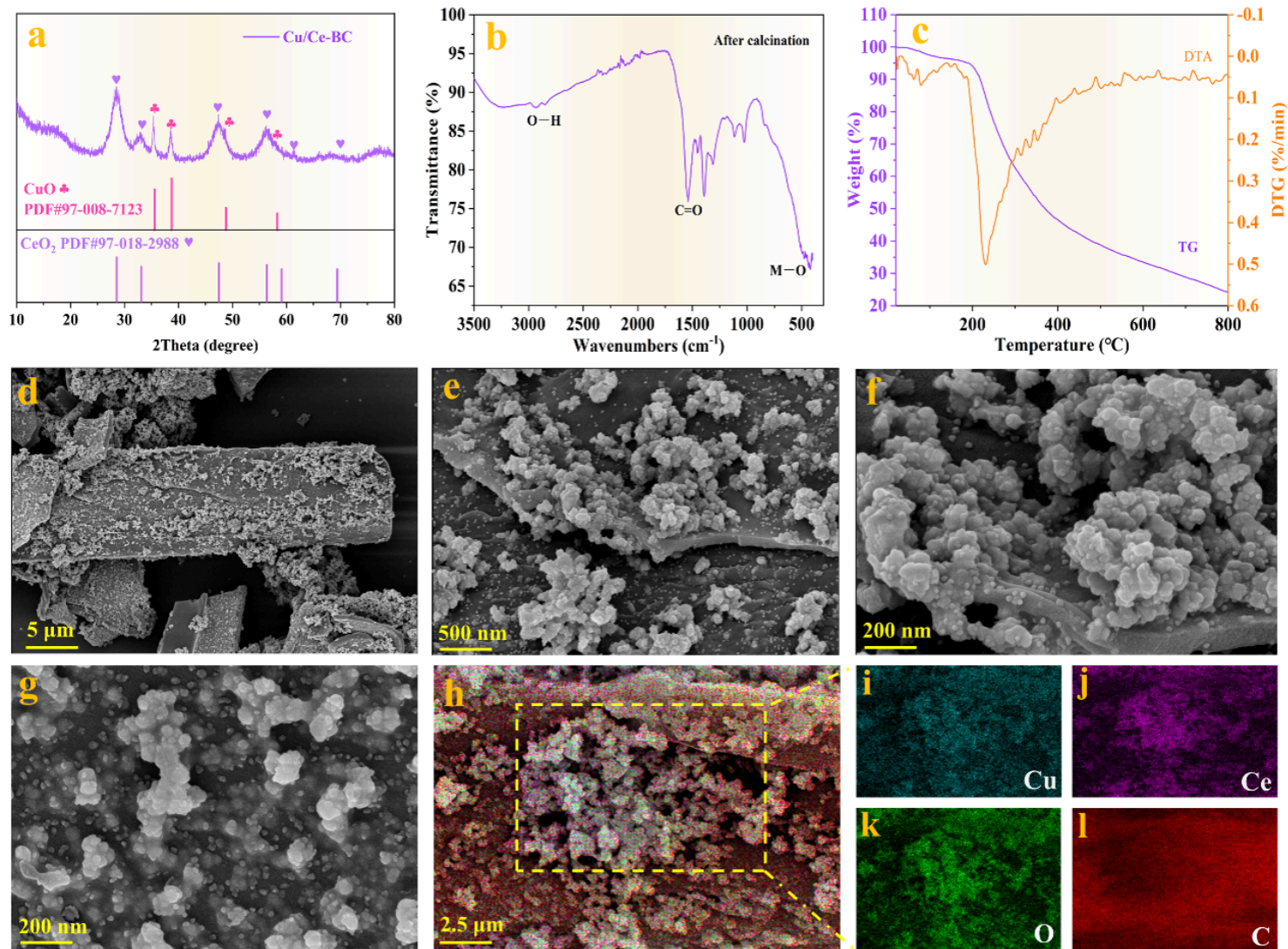


Figure 2

The XRD pattern (a) and FT-IR spectrum (b) of Cu/Ce-BC catalyst; TG-DTG curves of the modified bamboo charcoal precursor (c); SEM images (d-g) and EDS elemental distribution images (h-l) of Cu/Ce-BC

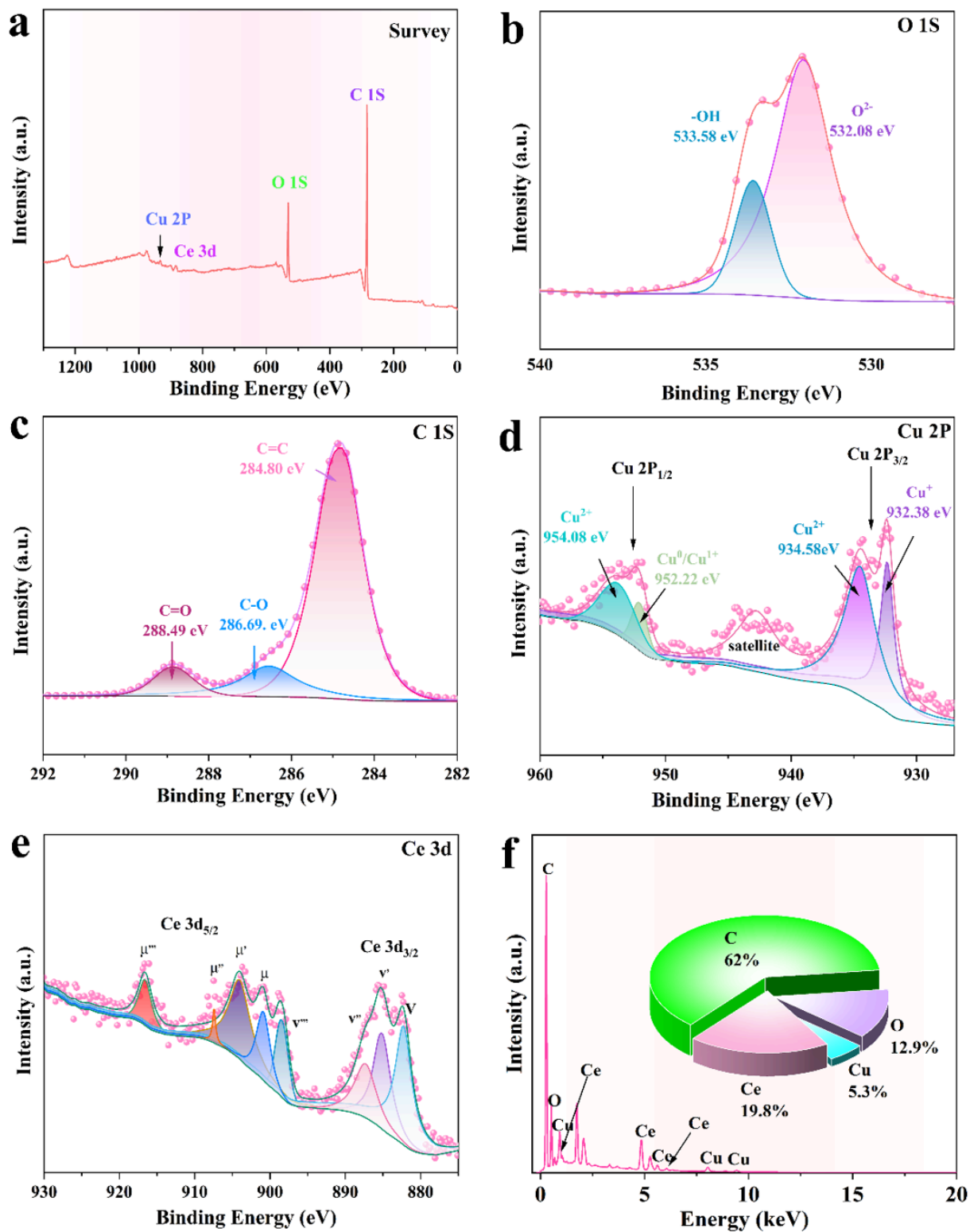


Figure 3

XPS survey (a), O 1s (b), C 1s (c), Cu 2p (d), and Ce 3d (e) spectra of the Cu/Ce-BC catalyst; (f) Elemental mass distribution of the Cu/Ce-BC catalyst.

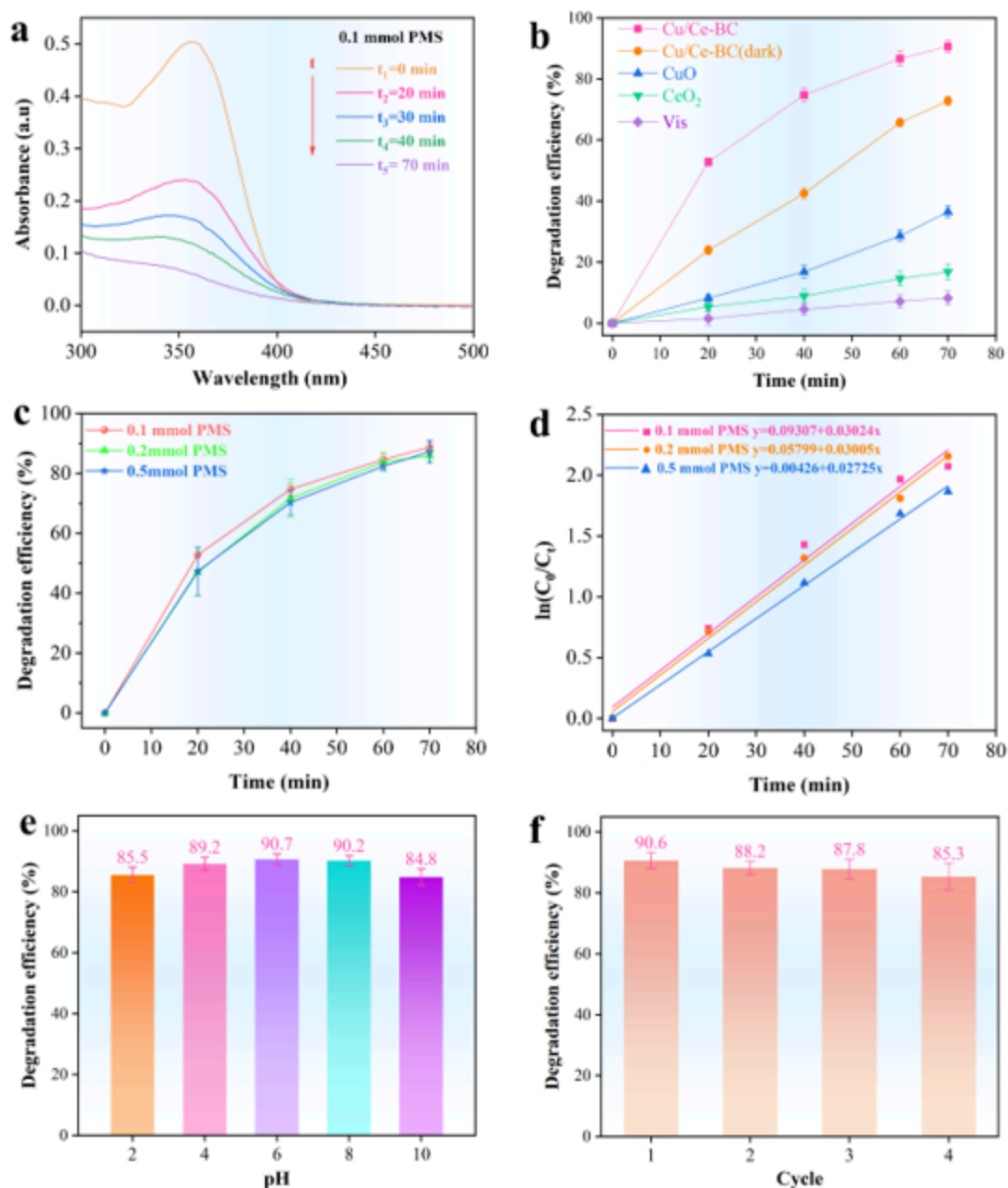


Figure 4

(a) UV-vis spectra of TC obtained at different reaction times (Cu/Ce-BC catalyst 40 mg, PMS 0.1 mmol, visible light); (b) the influence of different catalytic systems on the degradation efficiency of TC (catalyst 40 mg, PMS 0.1 mmol); The influence of initial PMS dosages on the degradation efficiency of TC (c), and the corresponding first-order kinetic fitting curves (d) (catalyst 40 mg, visible light); The influence of pH on the degradation efficiency of TC (e); Cycling performance of Cu/Ce-BC (f).

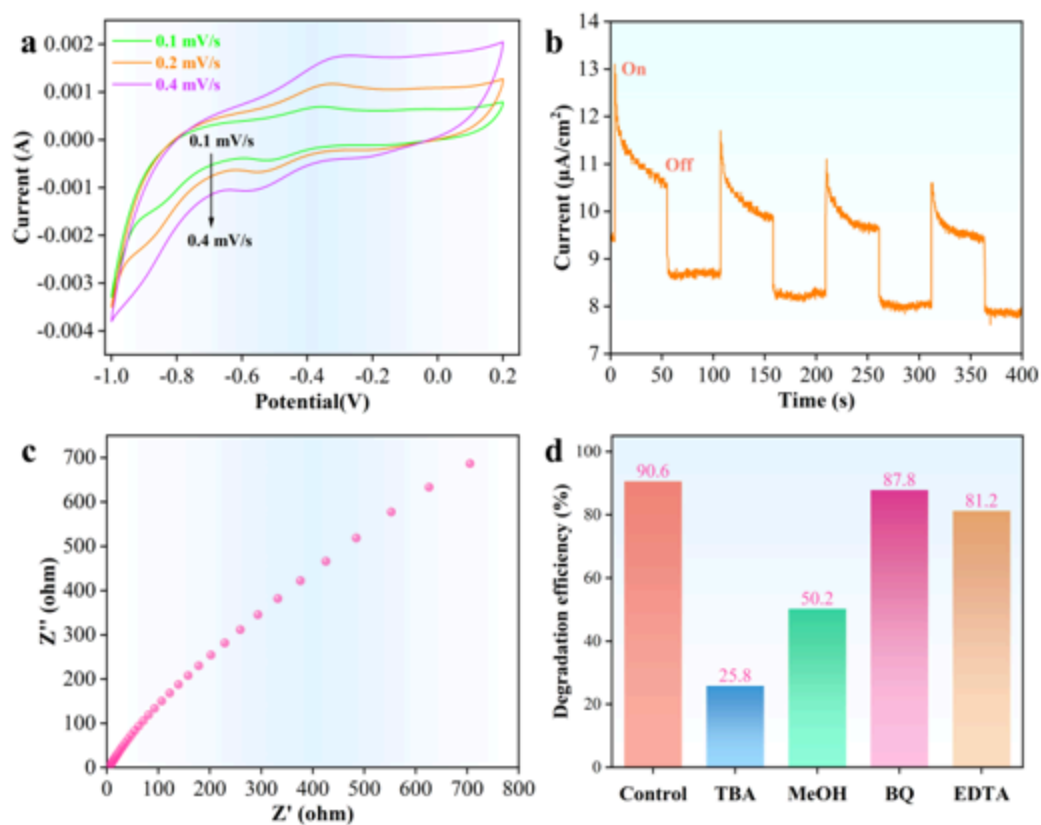


Figure 5

Electrochemical CV (a), photocurrent (b) and EIS (c) curves of Cu/Ce-BC catalyst; (d) Active radical scavenging experiment in Cu/Ce-BC/PMS system (catalyst 40 mg, PMS 0.5 mmol).

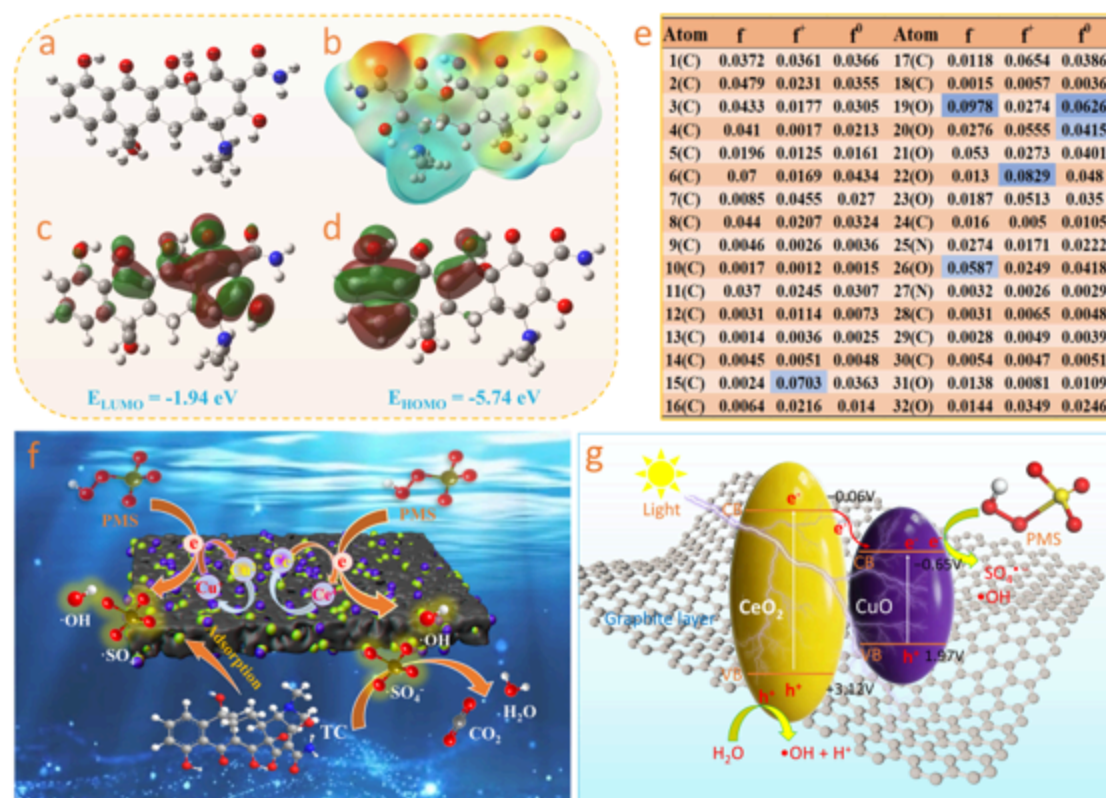


Figure 6

The optimized molecular configuration (**a**), the electrostatic potential (**b**), LUMO (**c**), HOMO (**d**) and Fukui indices (**e**) of TC molecule; The detailed degradation mechanism of TC in the Cu/Ce-BC/PMS system: the PMS activation mechanism (**f**), and the photocatalytic mechanism (**g**).

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