

Research on reuse of CTAB/EG composites after Cu(II) adsorption

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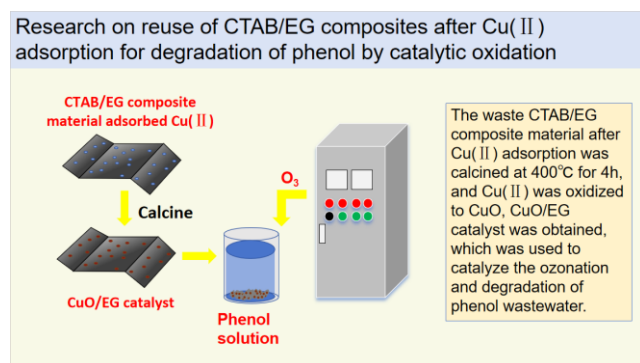
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Graphical abstract

The waste CTAB/EG composite material after Cu(II) adsorption was calcined at 400°C for 4h, and Cu(II) was oxidized to CuO, CuO/EG catalyst was obtained, which was used to catalyze the ozonation and degradation of phenol wastewater.



Abstract

A copper oxide (CuO)/ expanded graphite (EG) catalyst was prepared, characterized and used to catalyze ozonation process to improve the degradation of phenol wastewater. The morphology of CuO/EG catalyst, the types of functional groups and the structure of crystal surface were analyzed by X-ray diffraction, scanning electron microscopy, Fourier transform infrared spectroscopy and electron energy spectrum. To investigate its catalytic effect on phenol wastewater degradation by ozone. The key factors such as initial concentration of phenol, initial pH of solution and O₃ concentration were investigated. When the initial concentration of solution is 500 mg/L, the optimal initial pH value of solution is about 6, when the dosage of catalyst is 1.2 g/L and the concentration of ozone is 1.8 mg/L, the removal rate of phenol is 91.2% after 30 min reaction, which is more efficient and rapid than the single ozone degradation system. After 5 reactions, the removal rate of phenol reached about 92.0%, indicating that the catalyst had good stability and reusability. The results show that CuO/EG material can be used as an important

reusable resource for catalytic oxidation in the treatment of phenol wastewater.

Keywords: phenol; Ozone; Expanded graphite; CuO

1. Introduction

In recent years, the rapid development of industrialization and urbanization has led to increasingly severe water resource pollution, with industrial wastewater, agricultural non-point source pollution, domestic sewage, and emerging contaminants such as microplastics causing significant damage to aquatic ecosystems including rivers, lakes, groundwater, and marine environments. Statistical data indicates that approximately 20% of global freshwater fish species are threatened with extinction due to water pollution, while nearly 30% of the population in developing countries lacks access to safe drinking water. To combat these challenges, researchers have developed and implemented a range of treatment technologies encompassing physical methods like sedimentation and adsorption, chemical processes including advanced oxidation, biological remediation utilizing microbial and phytoremediation techniques, as well as integrated ecological engineering approaches such as constructed wetlands and sponge city infrastructure. These technological solutions are further supported by smart monitoring systems employing IoT and AI technologies for real-time water quality assessment, complemented by policy frameworks regulating pollutant discharge. Collectively, these multifaceted interventions have demonstrated significant effectiveness in improving water quality, restoring damaged ecosystems, and promoting the sustainable management of water resources. Raveena S. proposed a data-driven wastewater treatment optimization system combining IoT sensors, fuzzy logic (FE-RNN), and recurrent neural networks to enable safe reuse of treated water for coffee cultivation, promoting sustainable agriculture (Raveena *et al.* 2024.). Suresh M. developed a VisionPond system integrating IoT sensors and HG-RNN algorithms for real-time wastewater monitoring and treatment optimization, enabling polluted pond conversion into clean water sources through predictive process control (Suresh *et al.* 2025).

Phenol is an important chemical raw material, which can be used in the production of phenolic resin, pentachlorophenol, phenolphthalein and *n*-acetyl anisole and other chemical products, and also has important industrial applications in synthetic fibers, plastics, pesticides, dyes, coatings, etc. (Liang *et al.* 2016.). Phenol wastewater is a common pollutant in the above industries (Naeem *et al.* 2013; Sun *et al.* 2012). Phenol is highly toxic, carcinogenic, teratogenic and potentially mutagenic (Ahmadi *et al.* 2017), and is listed as one of the most important pollutants by the United States Environmental Protection Agency, with emission limits below 0.5mg/L. In addition, phenol in water is easily converted to chlorophenol during disinfection and oxidation, which is more carcinogenic and further exacerbates environmental and health hazards (Cheng *et al.* 2015). Therefore, it is very important to remove phenol from wastewater by efficient and environmentally friendly methods before it is discharged into the environment. At the same time, most of the preparation processes of various chemical materials will produce phenol or form phenol intermediates (Yang *et al.* 2021; Zhang *et al.* 2020; Carroll *et al.* 2020; Luo *et al.* 2021; Yuan *et al.* 2021). Phenol is toxic and corrosive, and exposure to concentrations of about 20 mg/L can be harmful to humans and animals (Lissaneddine *et al.* 2021; Qin *et al.* 2021; Martins *et al.* 2009). At present, researchers have tried different methods to degrade phenol-containing wastewater, including carbon bed adsorption, biological methods, electrochemical technology, membrane separation technology and other advanced oxidation technologies (Wang *et al.* 2008; Rauf *et al.* 2009; Jiao *et al.* 2019).

In recent years, various sewage treatment technologies have presented a new situation of contention (Zhao *et al.* 2021; Xue *et al.* 2021; Mao *et al.* 2021; Zhang *et al.* 2020; Chen *et al.* 2021; Zhou *et al.* 2022). Advanced oxidation technology (AOPs) stands out among many wastewater treatment technologies due to its high efficiency, speed, and convenience, and it continues to gain attention as its effectiveness is demonstrated in practice. Direct mineralization or oxidation of macromolecular refractory organic matter can improve the biodegradability of pollutants (Zhang 2020; Chen 2023). Additionally, AOPs offer significant advantages in treating trace harmful chemicals, such as environmental hormones, by completely mineralizing or breaking down most organic matter, demonstrating promising application prospects. AOPs can be broadly categorized into photochemical oxidation, catalytic wet oxidation, acoustochemical oxidation, ozone oxidation, electrochemical oxidation, and Fenton oxidation, among others. Chen N. used CN@PDA composites prepared by in-situ growth strategy for photocatalytic H₂O₂ production and in-situ H₂O₂ utilization in environmental purification work. Ozone is a highly oxidizing oxidizer with a high oxidation potential, second only to •OH (2.80V) and O• (2.42V). It can directly degrade polluting substances without additional conditions (Hoigne *et al.* 1983). Ozone has the advantages of small consumption, fast reaction, spontaneous decomposition into oxygen molecules, no pollution to the

environment, and unnecessary secondary treatment (Harufum *et al.* 2015). However, in experimental and industrial applications, ozone must be generated using an ozone generator under high-pressure conditions, which consumes significant amounts of electrical energy. In order to reduce power consumption, a large number of studies have shown that appropriate catalysts (Ma *et al.* 2010; Iaton *et al.* 2002; Zhang *et al.* 2019) can be added to accelerate the reaction and achieve a better catalytic effect of ozone degradation of pollutants in a short time. Therefore, the addition of a catalyst is essential to promote the ozone oxidation process for phenol degradation.

After reaching saturation adsorption, the adsorbent needs to be desorbed and regenerated before it can be reused to realize the reuse of waste adsorbent. Through reuse, the treatment cost and waste residue discharge can be reduced, while the adsorbent is recovered. At present, the regeneration methods of adsorbents include heating regeneration, pharmaceutical regeneration, wet oxidation regeneration and biological regeneration (Pan *et al.* 2016).

Inspired by the reuse of adsorbents, this work primarily utilizes waste CTAB/EG composite material after adsorbing Cu(II). Through high-temperature calcination, the adsorbed Cu(II) is thermally oxidized into CuO, forming a CuO/EG catalyst. The objective is to achieve resource utilization of waste adsorbents for enhancing the ozonation-based degradation of phenol wastewater. The goals include: (1) preparing and characterizing the CuO/EG catalyst using XRD, SEM, FTIR, and EDS techniques; (2) investigating its catalytic performance under varying operational conditions (e.g., initial phenol concentration, pH, and ozone dosage); and (3) evaluating the catalyst's stability and reusability over multiple reaction cycles. The motivation behind this study stems from the demand for cost-effective and sustainable catalysts that can improve ozonation efficiency while minimizing secondary pollution. The synergistic effect of EG's high surface area and CuO's redox properties enhances ozone activation, offering a potential solution for industrial wastewater treatment. The scope of this research focuses on optimizing catalytic ozonation for phenol removal, which holds significant implications for scaling up the process in practical applications.

2. Materials and Methods

2.1. Materials

CTAB/EG composite material after Cu(II) adsorption (He *et al.* 2023).

Phenol (C₆H₅OH) and potassium ferricyanide(K₃[Fe(CN)₆]) were acquired from Tianjin Kemiou Chemical Reagent Co., LTD. Ammonium chloride (NH₄Cl), ammonia water (NH₃·H₂O), sodium indigo disulfonate (C₁₆H₈N₂Na₂O₈S₂) bought from Shanghai Aladdin Reagent Co., LTD.

2.2. Methods

2.2.1. Preparation of CuO/EG composite

The waste CTAB/EG composite material after Cu(II) adsorption in the literature was calcined at 400 °C for 4 h,

and Cu(II) was oxidized to CuO to obtain CuO/EG catalyst, which was used to catalyze the degradation of phenol wastewater by ozone oxidation (He *et al.* 2023).

2.2.2. Experimental procedure

200 mL of phenol with a certain concentration was added to the self-made reactor. After adjusting the initial pH of the solution, quantitative catalyst was added to start the reaction. The initial concentration of phenol, initial pH value of the solution, O₃ concentration, catalyst dosage, reaction time and other factors were investigated experimentally. The solution samples were collected every 10 min and filtered into the volumetric bottle through the filter membrane. The concentration of phenol in the degraded solution was determined by spectrophotometry.

2.2.3. Analysis method

Method for determination of ozone concentration. The concentration of ozone was determined by indigo disulfonic acid spectrophotometry. The absorbance (A) and the absorbance (A₀) of blank test were measured at wavelength 610 nm. According to the following formula 1, the ozone concentration corresponding to different current currents can be obtained. Three parallel tests are carried out for each group, and the average value is the final measurement result.

$$\rho = \frac{(A_0 - A) \times 48 \times 50}{\epsilon \times b \times V} \quad (1)$$

Where: ρ is the mass concentration of ozone, g/L; A₀ is the blank absorbance; A is the absorbance of the sample; b is the thickness of the cupola, 1 cm; V is the volume of the water sample, mL. The molar absorptivity (ϵ) of sodium indigo disulfonate is 0.193×10^4 L/mol/cm.

Method for determination of phenol. Phenol was determined by 4-amino-antipyrine spectrophotometry with 1 g/L standard reserve solution, and the standard curve was $y = 5.459x - 0.05835$, $R^2 = 0.9998$.

3. Results and discussions

3.1. Characterization of catalyst

3.1.1. X-ray diffraction (XRD) analysis

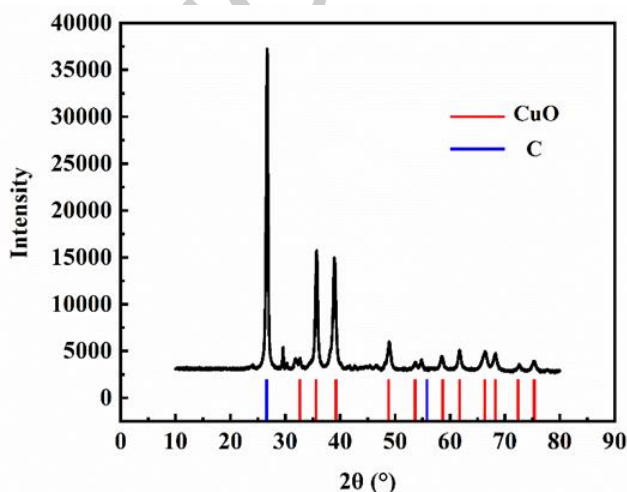


Figure 1. X-ray diffraction spectra of CuO/EG catalyst.

Figure 1 is the X-ray diffraction analysis diagram of CuO/EG catalyst. It can be seen from the Figure 1 that two characteristic peaks with high intensity and narrow width appear at $2\theta = 26.62^\circ$ and $2\theta = 55.78^\circ$, which correspond to the (002) crystal face and (004) crystal face of carbon element respectively. Due to the high carbon content in the CuO/EG catalyst, the carbon crystals exhibit a complete and well-ordered structure. Also, the CuO characteristic peak has a complete and high diffraction intensity. The characteristic peak of CuO is clear and well matched with the standard card (PDF#72-0629), indicating that CuO has a Monoclinic structure, high crystallinity and complete crystal structure. The narrow width of the characteristic peaks further indicates that CuO has large grain size and excellent crystallinity. In summary, it can be determined that the crystal phase of CuO is monoclinic crystal system, and it is uniformly dispersed on the surface of carbon carrier, and the crystallization is good. It is proved that the adsorbed Cu(II) can be oxidized to CuO by roasting at high temperature. At the high temperature of 400°C , organic matter is oxidized and decomposed, leaving only the diffraction peaks of CuO and elemental carbon in the XRD pattern.

3.1.2. Field emission scanning electron microscopy (SEM) analysis

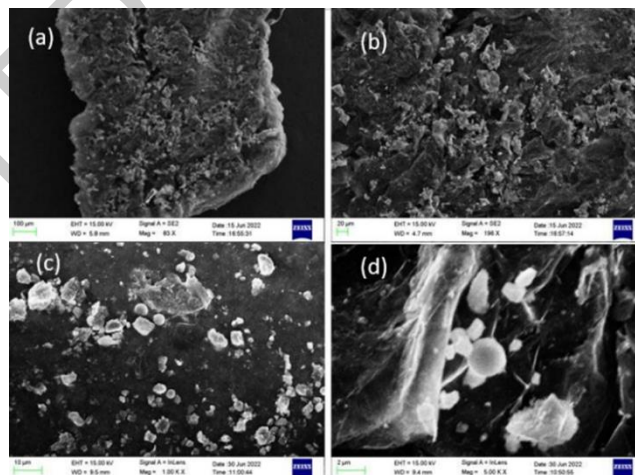


Figure 2. Field emission scanning electron microscopy of CuO/EG catalyst

The external morphology of the prepared CuO/EG catalyst was analyzed. Figure 2 shows the field emission scanning electron microscope analysis diagram of CuO/EG catalyst. Figure a shows that the external morphology of this composite material is the same as that of expanded graphite, both exhibiting a "wormlike" structure. However, the abundant pore structure and surface are filled with particulate matter and nearly covered, as shown in Figure b. More material is adsorbed to the surface and interior of the expanded graphite. According to the results of previous studies, the microscopic morphology of pure CuO is spherical. In Figure c and d, similar spherical substances can be observed, indicating that Cu(II) has been successfully oxidized into CuO through high-temperature roasting and is present on the surface of the expanded graphite.

3.1.3. Energy spectrum (EDS) analysis

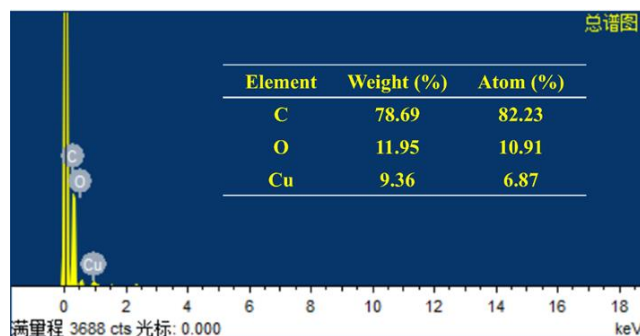


Figure 3 Energy spectrum analysis of CuO/EG catalyst

It can be seen in **Figure 3** that CuO/EG catalyst contains O and Cu in addition to C. The energy spectrum reveals that the C content is 78.69%, the O content is 11.95%, and the

Table 1. Specific surface area, average pore diameter and pore volume of CuO/EG catalyst

Materials	Specific surface area (m ² /g)	Mean aperture (μm)	Pore volume (mL/g)	Porosity (%)
CuO/EG	59.73	18.67	43.91	93.24

3.2. Phenol degradation experiment

3.2.1. Effect of initial pH value of solution on the removal of phenol

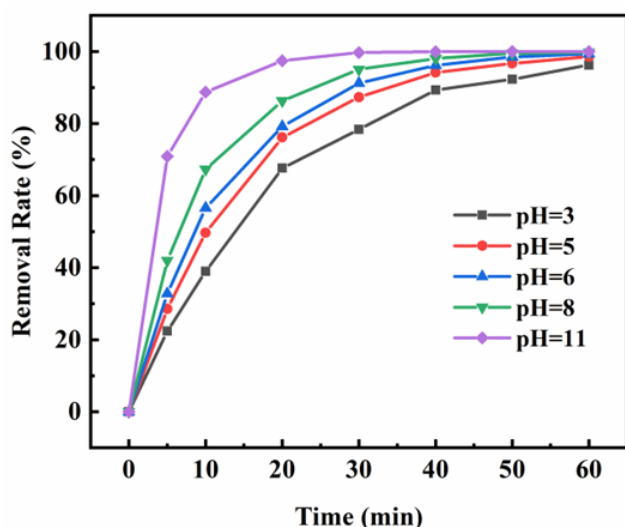


Figure 4. Effect of initial pH value on phenol degradation efficiency

The initial pH value of the phenol solution significantly influences the ozonolysis process and the surface characteristics of the catalyst, such as surface charge and proton transfer. Therefore, the initial pH value is a critical factor affecting the catalytic ozonization efficiency. This study was conducted in this section. 200 mL of 500 mg/L phenol solution with pH values of 3, 5, 6, 8 and 11 were respectively taken, the ozone concentration of the system was maintained at 1.8 mg/L, and the catalyst was added at 1.2 g/L. The experimental results were shown in **Figure 4**. As can be seen from **Figure 4**, with the increase of initial pH value of the solution, the removal rate of phenol also increases, showing a positive correlation. More alkaline solutions result in faster phenol removal. When pH value is 11, phenol removal rate reaches 100.0% after reaction

Cu content is 9.36%. This indicates that Cu(II) was successfully oxidized to CuO by high-temperature roasting method and existed on the surface of expanded graphite. The CuO/EG catalyst prepared by this method is free of other impurities and exhibits very high purity.

3.1.4. Specific surface area and pore size distribution

The pore structure of the material was analyzed using a mercury injection meter. As shown in **Table 1**, the specific surface area of CuO/EG material was 59.73m²/g, the average pore size was 18.76μm, and the pore volume was 43.91mL/g. The results show that the CuO/EG catalyst has a large specific surface area and a porosity of up to 93.24%, which can provide more active sites and has a strong catalytic ability.

for 30min. The catalyst is equivalent to promoting the decomposition of O₃ to produce •OH with stronger oxidation capacity under alkaline conditions, so as to degrade pollutants more efficiently, which is the most important reason for the best degradation under alkaline conditions (Afzal et al. 2019). The initial pH value of 300 mg/L phenol solution is about 6. As can be seen from the experimental data, when the pH value is 6, the phenol removal rate reaches 91.0% at 30 min and nearly 100.0% at 60 min. Good degradation effect was also obtained. For industrial applications, high degradation efficiency can be achieved within 30 min without adjusting the initial pH value, making the process more convenient. Therefore, under comprehensive consideration, the initial pH value of the optimal solution of the system is 6.

3.2.2. Effect of catalyst dosage on phenol removal

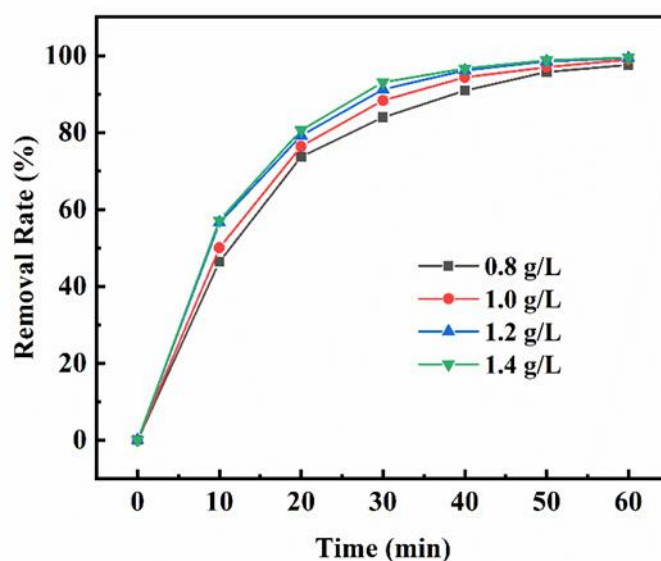


Figure 5 Effect of catalyst dosage on phenol degradation efficiency.

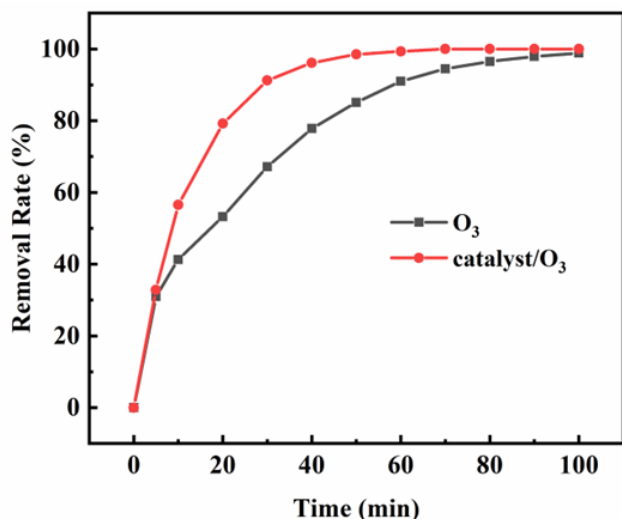


Figure 6 Influence of catalyst or not on phenol degradation

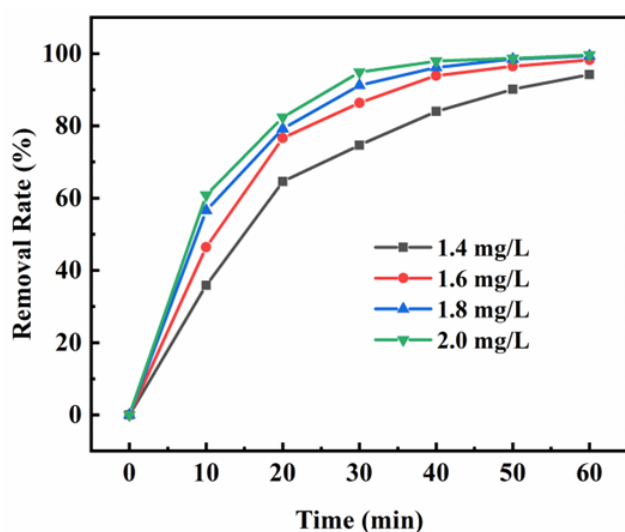


Figure 7 Effect of ozone concentration on phenol degradation efficiency

The dosage of catalyst plays an important role in the heterogeneous catalytic ozonation and degradation of pollutants. In this section, the effects of the dosage of CuO/EG catalyst at 0.8, 1.0, 1.2 and 1.4 g/L respectively on the catalytic ozonation of phenol degradation efficiency were studied. 200 mL of 500 mg/L phenol solution with initial pH value of 6 was taken, and the ozone concentration of the system was maintained at 1.8 mg/L. The experimental data analysis was shown in Figure 5. It can be seen from the experimental results in Figure 5 that the amount of catalyst added significantly influences the catalytic degradation efficiency. The catalytic degradation efficiency of phenol improves with increasing CuO/EG catalyst dosage, showing a positive correlation. As can be seen from Figure 6, the removal effect of the system with the addition of catalyst is 24.0% higher than that of ozone oxidation alone at 30 min, and at the same time, the removal rate reaches 100.0% at 60 min, while at 100 min alone, the removal rate reaches nearly 100.0%. It can be seen that the catalytic lifting effect of the catalyst is obvious, and the catalytic ozonation effect of phenol is good. Oxygen atoms on the catalyst surface combine with hydrogen ions in water to form hydroxyl, which can

provide more active sites for ozone adhesion. Therefore, the CuO contained in the catalyst can promote the decomposition of O₃, thereby rapidly starting the chain reaction of ozone decomposition and generating more •OH. When the dosage of catalyst increased from 1.2 g/L to 1.4 g/L, the removal rate of phenol increased from 91.2% to 92.0% for 30 min. Considering the amount of catalyst used and removal effect, the dosage of CuO/EG catalyst was selected as 1.2g /L for a series of experimental analysis.

3.2.3. Effect of ozone concentration on phenol removal in solution

The level of ozone concentration is a fundamental factor affecting the removal of phenol pollutants in the system. Therefore, this experiment was conducted to study and analyze the effect of ozone concentration on phenol removal. 200 mL of 500 mg/L phenol solution with pH value of 6 was selected, and 1.2 g/L catalyst was added. The ozone concentration in the solution was adjusted to 1.4, 1.6, 1.8, and 2.0 mg/L to explore the effects of different ozone concentrations on phenol removal, as shown in Figure 7. As can be seen from Figure 7, the phenol removal efficiency improves with increasing ozone concentration. When the ozone concentration is 1.4 mg /L and 1.6 mg /L, the removal rate of phenol corresponds to 76.6% and 86.4%, respectively, 30 min after reaction. When the ozone concentration is more than 1.8 mg/L, the removal rate of phenol in the catalytic ozone oxidation system can reach more than 90% after reaction for 30 min. It can be seen that due to its strong oxidation, ozone is still the main factor affecting the degradation of phenol. When the ozone concentration increased from 1.8 mg/L to 2.0 mg/L, the removal rate increased from 91.1% to 94.9%, with a small increase. Considering the ozone concentration and removal rate, the ozone concentration of 1.8 mg/L was selected for a series of experimental analyses.

3.2.4. Effect of initial concentration of solution on removal of phenol

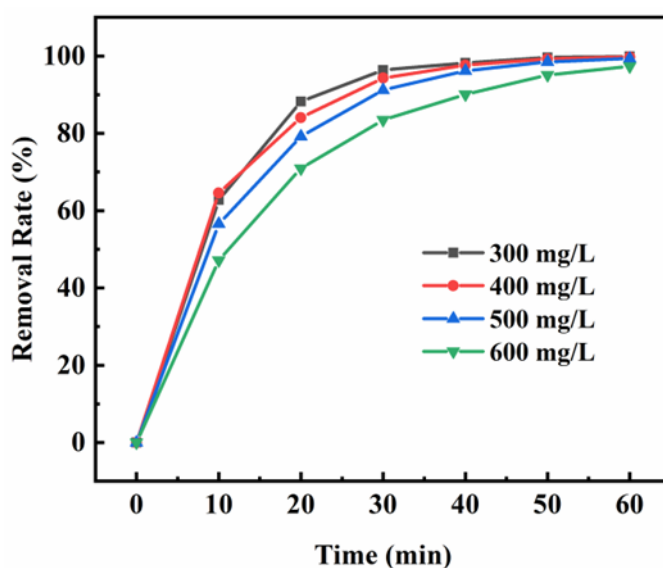


Figure 8. Effect of initial solution concentration on phenol degradation efficiency

The concentrations of phenol pollutants in rivers, lakes and other water bodies are different, so the study of phenol solutions with different initial concentrations is of reference significance for the actual degradation of phenol wastewater. In this section, phenol solutions with initial concentrations of 300 mg/L, 400 mg/L, 500 mg/L, and 600 mg/L were used to conduct catalytic ozonation degradation experiments, and the relationship between the initial concentration and removal rate of phenol containing wastewater was analyzed. 200 mL of phenol solution with initial pH of 6 was taken, maintain the concentration of ozone in the system at 1.8 mg/L, and dosage of catalyst at 1.2 g/L. The experimental results are shown in **Figure 8**. With the increase of the initial concentration of phenol, the catalytic degradation effect gradually deteriorates. When the initial concentration of the solution increases from 300 mg/L to 400 mg/L, 500 mg/L and 600 mg/L, 30 min after the reaction, The removal rates of phenol in the catalytic ozone oxidation system decreased from 96.4% to 94.3%, 91.2% and 83.5%, respectively. Lower concentrations are more favorable for the degradation of phenol pollutants. This is because, as the initial concentration increases, the number of pollutant molecules increases, leading to insufficient active sites on the catalyst surface for effective degradation. Consequently, the removal rate of pollutants decreases.

3.2.5. Stability of catalyst

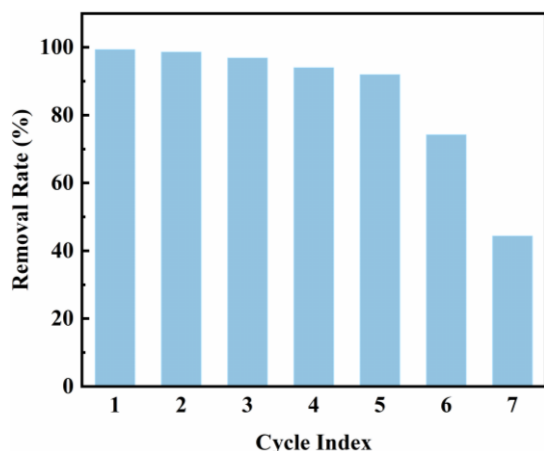


Figure 9. Effect of repeated use of CuO/EG catalyst on phenol removal rate

In order to evaluate the long-term stability and reuse performance of CuO/EG catalyst, seven consecutive phenol degradation experiments were carried out. The experimental results show that the degradation efficiency of the catalyst decreases gradually with the increase of The Times of use. The degradation efficiency of phenol gradually decreased from 99.4% in the first experiment to 92.0% in the fifth experiment, and further decreased to

74.21% and 44.35% in the sixth and seventh experiments. Although the catalytic efficiency decreased with the increase of the number of uses, the degradation efficiency remained above 90% in the first five cycles, indicating that the CuO/EG catalyst had good stability during repeated use.

3.3. Hydroxyl masking experiment

In order to investigate the role of hydroxyl radical ($\cdot\text{OH}$) in catalytic ozonation of phenol, the inhibitor experiment was conducted, using tert-butanol (TBA) as the trapping agent of $\cdot\text{OH}$. Tert-butanol is a commonly used $\cdot\text{OH}$ inhibitor, which can effectively capture $\cdot\text{OH}$ and inhibit its participation in the reaction.

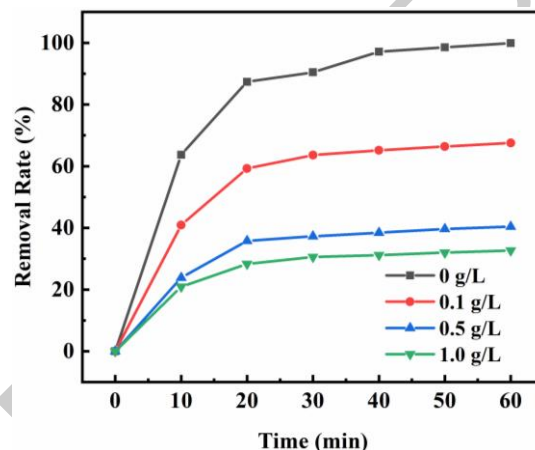


Figure 10. Effect of tert-butanol concentration on phenol degradation efficiency.

The contribution of hydroxyl radical ($\cdot\text{OH}$) to the degradation of pollutants was systematically evaluated by the inhibitor experiments of different concentrations of tert-butanol (0 g/L, 0.1 g/L, 0.5 g/L, 1.0 g/L). The experimental results show that with the increase of tert-butanol concentration, the production of $\cdot\text{OH}$ is gradually inhibited, and the removal rate of pollutants is also significantly decreased. When no tert-butanol was added, the removal rate of pollutants reached 99.89%. When the concentration of tert-butanol increased to 1.0 g/L, the removal rate decreased to 32.68%. This trend clearly indicates that $\cdot\text{OH}$ is the main active species in pollutant degradation, and its contribution decreases significantly with the increase of inhibitor concentration.

In addition, by comparing the removal rate changes at different time points (for example, at 30 minutes, the removal rate at 0 g/L and 1.0 g/L tert-butanol was 90.43% and 30.57%, respectively), it was further confirmed that $\cdot\text{OH}$ played a key role in both the early and middle stages of the reaction.

3.4. Effect of initial pH on the degradation kinetics of phenol

Table 2. Fitting results of phenol degradation kinetics at different initial concentrations

pH	Rate equation	R ²
3	$-\ln(C/C_0)=0.05395t-0.01377$	0.996
5	$-\ln(C/C_0)=0.06984t-0.00317$	0.999
6	$-\ln(C/C_0)=0.08386t-0.03931$	0.999
8	$-\ln(C/C_0)=0.10188t+0.00673$	0.998
11	$-\ln(C/C_0)=0.18642t+0.17726$	0.998

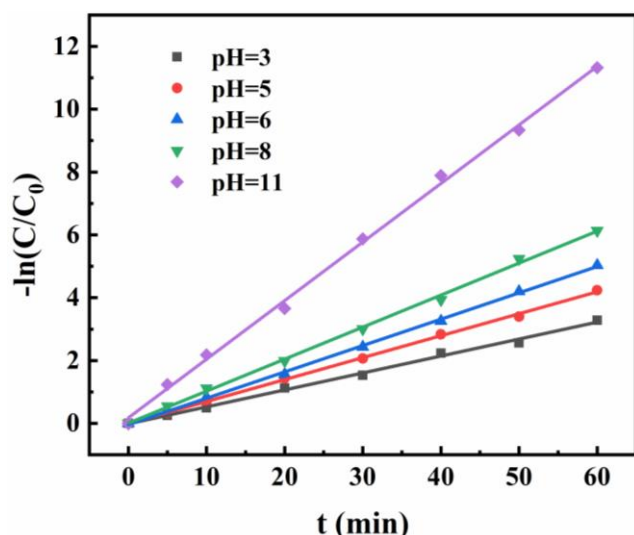


Figure 11. Fitting of phenol degradation kinetics at different initial pH

As can be seen from **Figure 11**, the experimental results fit well with the first-order reaction kinetics. As can be seen from Table 2, with the increase of pH value, the reaction rate constant gradually increases from 0.05395 s^{-1} to 0.18642 s^{-1} , and the correlation coefficients R^2 are all above 0.99, indicating that pH is in the range of 3-11. The ozonation of phenol containing wastewater catalyzed by CuO/EG catalyst conforms to the first-order reaction kinetics.

4. Conclusion

In this study, the waste CTAB/EG composite material adsorbed Cu(II) was oxidized by high-temperature roasting to produce CuO/EG catalyst, which was used to catalyze ozone oxidation of phenol wastewater. The initial concentration of phenol, the initial pH value of solution, the concentration of O_3 , the dosage of catalyst and the reaction time all have effects on the catalytic oxidation process. Based on the experimental results, the optimal initial phenol concentration for the system is 500 mg/L, and the optimal initial pH value is approximately 6. When the catalyst dosage is 1.2 g/L and the ozone concentration is 1.8 mg/L, the removal rate of phenol after 30 min reaction is 91.2%, significantly higher than that achieved by ozone oxidation alone. At 30 min, the degradation was increased by 24.0%, and the degradation was faster than that of ozone alone. It can be seen that the catalytic ozonation of phenol with catalyst has a good effect. After 5 reactions, the removal rate of phenol reached about 92.0%, indicating that the catalyst had good stability and reusability.

In order to more accurately evaluate the performance of CuO/EG catalysts compared with other catalytic degradation materials for phenol, we systematically reviewed and collated the literature in related fields. Zhou B. *et al.* prepared a series of high-performance catalysts by regulating the morphology of cerium oxide (CeO_2) to catalyze the ozonation and degradation of phenol. The results showed that the optimized morphology of CeO_2 catalyst achieved complete mineralization of phenol

within 30 minutes, and the removal rate reached 100% (Zhou *et al.* 2024). Gao E. H. *et al.* screened bimetallic CuCeO_2 -BTC from a series of MOF-derived MCeO_2 -BTC ($\text{M} = \text{La}, \text{Cu}, \text{Co}, \text{Fe}$ and Mn) catalysts and systematically studied the effect of Cu/Ce ratio on catalytic ozonation of phenol removal. The results showed that $\text{Cu}_2\text{Ce}_1\text{O}_y$ -BTC achieved phenol mineralization efficiency of nearly 100% within 200 minutes (Gao *et al.* 2025). Moussavi G. *et al.* studied the effect of MgO nanocrystalline powder on phenol removal from saline wastewater during catalytic advanced oxidation. The experimental results show that under the optimal condition of pH = 7, using 4 g/L catalyst, the removal rate of phenol reaches 96% and the removal rate of COD reaches 70% after 80 minutes (Moussavi *et al.* 2010). In this study, CuO/EG catalyst was prepared using waste adsorbent CTAB/EG to catalyze the degradation of phenol by ozone oxidation. The experimental results showed that under the optimal conditions (initial pH = 6, catalyst dosage of 1.2 g/L, ozone concentration of 1.8 mg/L), the removal rate of phenol reached 91.2% within 30 minutes. In addition, the removal rate of the catalyst remained at about 92% after 5 cycles of use. Compared with the three materials mentioned above, CuO/EG catalyst not only shows efficient catalytic performance, but also shows excellent stability and environmental friendliness, which makes it have significant advantages in practical applications.

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CRedit authorship contribution statement

Jun He: Conceptualization, Funding acquisition, Resources, Writing – original draft. **Jiaqi Chen:** Formal analysis, Validation, Writing – original draft. **Meng Yuan:** Data curation, Methodology, Project administration, Writing – original draft. **Tao Song:** Investigation, Visualization, Writing – review and editing. **Jianing Dou:** Software, Writing – review and editing. **Xuan Lin:** Supervision, Writing – review and editing.

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.

Data availability

Data will be made available on request.

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