

## Removal of Ciprofloxacin in Wastewater by Catalytic Ozonation Using Magnetite-supported Alginate as a Catalyst

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### Abstract

This research investigated the removal of ciprofloxacin (CIP) in wastewater by catalytic ozonation using magnetite-supported alginate as a catalyst. The catalyst was synthesized by incorporating Fe<sub>3</sub>O<sub>4</sub> nanoparticles, sludge ash, and iron filings onto an alginate support, and then characterized by Fourier-transform infrared spectroscopy (FT-IR) to confirm the presence of magnetite on the alginate support. A venturi-type ozonation system, with an ozone production rate of 66 mg/h, was employed under varying conditions, including CIP concentrations (1 - 10 mg/L), pH (5 - 9), catalyst dosages (0.2 - 1.0 g/L), and contact times (0 - 60 min). Under optimal conditions (5 mg/L CIP, pH 5, 0.7 g/L catalyst, 60-minute contact time), a removal efficiency of 85.61% was achieved, compared to 70.49% with ozonation alone. The enhanced performance of the catalyst was attributed to its ability to generate hydroxyl radicals with higher oxidation potential than ozone (•OH). Kinetic study indicated that both catalytic ozonation and sole ozonation followed a second-order reaction model, with rate constants (k) of 0.0198 and 0.0081 (mg/L)<sup>-1</sup> min<sup>-1</sup>, respectively. The catalyst exhibited effective reusability, maintaining over 85% efficiency after five cycles. This study highlights the potential of magnetite-supported alginate catalyst as a sustainable, cost-effective solution for removing antibiotic contaminants from wastewater.

Keywords: Antibiotic; Catalytic ozonation; Ciprofloxacin; Magnetite-supported alginate

### 1. Introduction

Ciprofloxacin (CIP) is an antibiotic agent in the fluoroquinolone class, with antibacterial properties against both gram-positive and gram-negative bacteria. It is widely used in the treatment of tuberculosis, gastrointestinal, urinary tract and respiratory tract infections of humans and as veterinary medicine to prevent or treat infectious diseases. However, CIP that is ingested into the body is partially absorbed and can be excreted from the body through urine and feces, accounting for up to 72% in a pharmacologically active form (Division of Epidemiology, 2022; Zhang et al., 2019). The contamination of wastewater with CIP, which is then discharged into local sewage systems or directly into natural water sources, leads to pollution of the environment. This causes various impacts, such as the development of antimicrobial resistance in microorganisms, and disruption of the aquatic ecosystem Therefore, wastewater treatment systems are necessary to remove the CIP in wastewater before being released into the environment (Kumhomkul, 2020).

Typically, the wastewater treatment systems of communities and public healthcare predominantly use activated sludge process. This biological wastewater treatment process utilizes microorganisms to decompose various organic substances. However, such antibiotics possibly deteriorate the performance of the microorganisms. For CIP, only the piperazine ring is degraded, while the active quinolone structure remains unchanged, allowing it to inhibit microbial activity in the treatment system, which impacts the efficiency of biological wastewater treatment systems (Chen et al., 2021). Physical treatments, such as adsorption, can treat high concentrations of organic compounds and antibiotics, but the used adsorbent is required a proper handling, otherwise antibiotics may leach back into the environment (Gahrouei et al., 2024). Membrane technology, such as nanofiltration (NF), can effectively treat residual contaminants in wastewater. However, a limitation is membrane fouling, leading to a reduction in permeate volume and increase of O&M cost (Yin et al., 2024). The ozonation process is a chemical process that uses ozone to oxidize organic and inorganic contaminants in water. Ozone is a powerful oxidizing agent capable of decomposing recalcitrant pollutants. Furthermore, when comparing toxicity, it is found that ozone does not result in any residual substances after treatment (Derco et al., 2018). However, ozonation process has limitation in selectivity toward pollutants. Catalytic ozonation, an advanced oxidation process (AOP), overcomes this limitation by generating highly reactive hydroxyl radicals (•OH) with a higher oxidation potential than ozonation alone (Lopez-Frances et al., 2023).

Heterogeneous catalytic ozonation is designed to enhance the degradation of recalcitrant organic pollutants through hydroxyl radical generation. This process combines ozonation with the oxidative properties of solid metal oxides to achieve effective degradation and mineralization of organic contaminants (Chookaew et al., 2024). Key factors influencing its efficiency include the stability, durability, recovery, and reusability of the catalyst after treatment. Studies have shown that metal oxides (e.g., NiO, Fe<sub>2</sub>O<sub>3</sub>, MnO) supported on mesoporous materials (e.g., alumina, silica, zeolite) are highly effective catalysts for catalytic ozonation (Kruanak and Jarusutthirak, 2019). Metal oxides, like Fe<sub>3</sub>O<sub>4</sub>, are of growing interest due to their low cost, stability, and effectiveness in wastewater treatment, especially for antibiotics. However, iron

oxide may release fine particles into treated water, posing environmental risks if it cannot be recovered and reused (Davies et al., 2001; Li et al., 2022; Mahmoudi et al., 2024). Entrapping iron in a polymer matrix or solid support retains its reactivity and makes recovery easier. Immobilizing iron could also solve issues related to iron precipitate formation at higher pH. Sodium alginate, a porous organic polymer, is an inexpensive natural substance with a negative charge, high water affinity, and abundant carbonyl and hydroxyl groups, making it a suitable catalyst support material (Ahmad et al., 2023). The use of Fe<sub>3</sub>O<sub>4</sub> nanoparticles, sludge ash, and iron filings on alginate supports enhances the stability of the catalyst, strengthening the alginate matrix and preventing breakage during treatment (Ayed et al., 2023).

This study focuses on enhancing ozonation process for removal CIP in wastewater using a catalyst made from magnetite supported on alginate. The catalyst was synthesized by incorporating Fe<sub>3</sub>O<sub>4</sub> nanoparticles, ash sludge, and iron filings into the alginate matrix. Factors affecting treatment efficiency, including CIP concentration, pH, catalyst dosage, and contact time, were investigated. The study also examines reaction kinetics of CIP degradation by catalytic ozonation, compared with ozonation alone. The findings provide insights into optimal conditions for effective catalyst to treat CIP and other antibiotic contaminants in the wastewater.

### 2. Methodology

#### 2.1 Chemicals

In this experiment, ferrous sulphate heptahydrate (FeSO<sub>4</sub>·7H<sub>2</sub>O), sodium dihydrogen phosphate (NaH<sub>2</sub>PO<sub>4</sub>·2H<sub>2</sub>O), disodium hydrogen phosphate (Na<sub>2</sub>HPO), sodium hydroxide (NaOH), and potassium iodide (KI) were obtained from KemAus (Australia). Ferric chloride hexahydrate (FeCl<sub>3</sub>·6H<sub>2</sub>O), and sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) were purchased from Qrec (New Zealand). Sodium thiosulfate (Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub>) and calcium chloride dihydrate (CaCl<sub>2</sub>·2H<sub>2</sub>O) were obtained from Ajax Finechem (Australia). All mentioned chemicals used were of analytical grade, while sodium alginate  $(C_6H_7NaO_6)$  was of commercial grade.

#### 2.2 Preparation of catalyst

In this research, magnetite nanoparticle  $(Fe_3O_4)$  was synthesized as a catalyst. Iron filings, sludge ash from wastewater treatment systems were also used in conjunction with magnetic substances to increase the strength and durability properties of the catalyst. The steps of catalyst preparation are shown in Figure 1.

## 2.2.1 Synthesis of magnetite nanoparticle (Fe<sub>3</sub>O<sub>4</sub>)

The co-precipitation method was used to prepare Fe<sub>3</sub>O<sub>4</sub> nanoparticles (Mahmoudi et al., 2024). A mixture of 4.72 g of FeCl<sub>3</sub>·6H<sub>2</sub>O and 1.72 g of FeSO<sub>4</sub>·7H<sub>2</sub>O was dissolved in 100 mL of distilled water. The solution was then adjusted to a basic pH by adding 10 M NaOH until the pH reached 9-10, which was indicated by a color change from light brown to dark black. The mixture was stirred using a hotplate magnetic stirrer at 80 °C for 1hour. During this step, the particles transformed into Fe<sub>3</sub>O<sub>4</sub> nanoparticles, which are magnetite. An external magnet was then used to attract these particles out of the solution, and they were subsequently washed with distilled water and ethanol before being dried at 60 °C (Mahmoudi et al., 2024).

#### 2.2.2 Preparation of sludge ash

Sludge obtained from a wastewater treatment plant was dried and then heated for 1 hour at a temperature of 105 °C. Afterward, it was ground and subjected to calcination at a temperature of 550 °C for 2 hours. The material was then allowed to cool in a desiccator.

# 2.2.3 Preparation of magnetite-supported alginate (magnetite/alginate)

Magnetite-supported alginate was synthesized by using the ionic gelation method (El-Shamy *et al.*, 2019). A mixture of 1.0 g of sludge ash and iron filings in a 2:1 ratio, along with iron oxide nanoparticles (Fe<sub>3</sub>O<sub>4</sub>), was added to 100 ml of distilled water and mixed using a magnetic stirrer for 60 minutes to achieve homogeneity. To prepare the magnetitesupported alginate, 1.0 g of sodium alginate was added to the previous mixture and stirred at high speed for 2 hours until it was confirmed that the solution was homogeneous and free of bubbles. The resulting mixture was then dripped into a 0.1 M calcium chloride solution that was being stirred with a magnetic stirrer. When the previous mixture reacted with calcium chloride, cross-linking occurred, resulting in the formation of uniform spherical nanocomposites (magnetite/calcium alginate). The mixture was left in the solution for 24 hours to complete the polymerization reaction. After that, the catalyst was thoroughly washed with distilled water several times to remove unreacted calcium ions and dried at 60 °C, left overnight, and stored in a dark place (Ayed et al., 2023). As-prepared catalyst was characterized using Fourier Transform Infrared Spectroscopy (FT-IR) to confirm the presence of magnetite on the alginate support.

#### 2.3 Preparation of synthetic wastewater

Synthetic wastewater was prepared from the commercial CIP antibiotic under the trade name Loxcipro 500 mg. The tablets were crushed into a fine powder using a mortar and pestle. The powder was then dissolved in distilled water using a magnetic stirrer. It was filtered through glass fiber filters (GF/C), and the volume was adjusted to 1L. This resulted in a CIP solution with a concentration of 500 mg/L, which was used as a stock solution for the designated concentrations in the experiments. The CIP concentration in synthetic wastewater was analyzed using a UV-Vis spectrophotometer at a wavelength of 274 nm (Baldez et al., 2024). A calibration curve was prepared from standard CIP obtained from the Department of Medical Sciences, Thailand. The standard solution of 50 mg/L was prepared and diluted with distilled water to create different concentrations of 0, 0.63, 1.25, 2.5, 5, 10, and 20 mg/L.

## 2.4 Installation and operation of venturi-type ozonation system

Batch experiments were carried out using a venturi-type ozonation system with an ozone generator of 66.0 mg/hr. The rectangular reactor was made of acrylic with a dimension of 12 x 12 x 15 cm<sup>3</sup> and a total capacity of 2 L. Synthetic wastewater containing CIP was circulated using a pump through a venturi ejector where a vacuum was created. At this point, ozone gas was fed in and mixed with the wastewater before the ozonated wastewater was recirculated to the reactor, as shown in Figure 2. Unreacted ozone gas was captured in sodium thiosulfate (Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub>) solution before being released.

Factors affecting CIP removal efficiency, including contact times (0-60 min), pH (5, 7, 9), initial concentration of CIP (1, 5, 10 mg/L), and catalyst dosage (0.2, 0.5, 0.5)0.7, 1.0 g/L), were investigated. Two sets of experiments including ozonation alone and catalytic ozonation were conducted at the same conditions. An aliquot sample of 25 mL was collected at designated reaction time, and then, analyzed for CIP concentration using a UV-Vis spectrophotometer at a wavelength of 274 nm. (Baldez et al., 2024). The CIP removal efficiency was calculated according to Equation 1. The results were used to evaluate the effectiveness of the magnetite-supported alginate catalyst in enhancing CIP removal efficiency.



Figure 1. Synthesis process of magnetite-supported alginate



Reagent bottle

Figure 2. Installation of venturi-type ozonation system

Removal efficiency (%) =  $\left[\frac{\text{CIP}_0 - \text{CIP}_t}{\text{CIP}_0}\right] \times 100$  (1)

where;  $CIP_0$  represents the initial CIP concentration in wastewater (mg/L) and  $CIP_t$  represent the concentration of CIP measured at a given time (mg/L).

#### 2.5 Study of chemical kinetic of reaction

The study of the reaction kinetic compares the reaction rates of ozonation and catalytic ozonation processes in degradation of CIP under the optimal conditions. Linear relationship between the CIP concentration and the reaction time was plotted and compared with the reaction order model as shown in equations 2, 3, and 4. The analysis considered the R<sup>2</sup> value that was closest to 1. Subsequently, the reaction rate constant (k) was determined from the slope of the linear equation.

Zero-order reaction  $[CIP]_t = [CIP]_0$ -kt (2)

First-order reaction  $\ln[CIP]_t = \ln[CIP]_0$ -kt (3)

Second-order reaction  $\frac{1}{[CIP]_t} = \frac{1}{[CIP]_0} + kt$  (4)

where;  $[CIP]_0$  and  $[CIP]_t$  represent the concentration of CIP at the initial time and at any time t, respectively, while k is the rate constant for the reaction of CIP removal and t is the reaction time (min).

#### 2.6 Study of reusability of the catalyst

To study the reusability of catalyst, used catalysts were collected from the reactor using magnetic separation. The catalysts were cleaned with an ultrasonic cleaner at 20 - 80 kHz in distilled water, followed by drying at 60 °C before reuse in subsequent experiments for five cycles under the same conditions.

### 3. Results and Discussion

3.1 Characterization of magnetite-supported alginate as a catalyst

The magnetite-supported alginate catalyst was prepared using the ionic gelation method from iron oxide  $(Fe_3O_4)$ nanoparticles, sludge ash, and iron filings mixed with sodium alginate ( $C_6H_7NaO_6$ ). When reacted with calcium chloride (CaCl<sub>2</sub>), an ionic gelation process occurred between calcium ions (Ca<sup>2+</sup>) and the sodium alginate chains, forming spherical calcium alginate (C<sub>6</sub>H<sub>7</sub>NaO<sub>6</sub>) nanocomposites. After being left overnight, the catalyst appeared as black spheres with dense magnetic particles inside, as shown in Figure 3(a), confirming effectiveness of alginate as a support material. Upon drying in a hot air oven, moisture loss of 89.82% resulted in brown-black spherical particles approximately 1 - 2 mm in size, with a rough and irregular surface, as depicted in Figure 3(b). The magnetitesupported alginate exhibited magnetic responsiveness, as shown in Figure 3(c). This property enabled efficient catalyst recovery using a magnetic field, facilitating its separation from treated wastewater, as illustrated in Figure 3(d).

The FT-IR results exhibit the functional groups of the magnetite-supported alginate, as shown in Figure 4. The peak at a wave number of 3386.25 cm<sup>-1</sup> represents the frequency of the stretching vibration of the O - H bond from the hydroxyl group, which arises from the alginate chain and the Fe<sub>3</sub>O<sub>4</sub> nanoparticles. The peak at 1604.35 cm<sup>-1</sup> indicates the asymmetric and symmetric vibrations of the C = O bond, corresponding to the functional groups of carboxylic acid (-COO-) in alginate or the O-H bond vibrations in Fe<sub>3</sub>O<sub>4</sub> nanoparticles. The peak at 1036.01 cm<sup>-1</sup> results from the stretching vibrations of the single C-O and C-O-C bonds. The peaks at 583.49, 513.02, and 481.14 cm<sup>-1</sup> indicate the stretching vibrations of the O-Fe-O functional groups present in Fe<sub>3</sub>O<sub>4</sub> nanoparticles and iron filings, which play a crucial role in the ozonation process using magnetite supported on alginate as a catalyst. The FT-IR analysis results of Fe<sub>3</sub>O<sub>4</sub> nanoparticles is consistent with that from the research of Ayed et al. (2023).



**Figure 3.** Magnetite-supported alginate for use as catalyst (a) before drying, (b) after drying at 60 °C, (c) magnetic property of catalyst, and (d) separation of catalyst from water by magnet



Figure 4. FT-IR spectra of magnetite-supported alginate

## 3.2 Factors affecting CIP removal efficiency by ozonation alone

To investigate the factors affecting CIP removal efficiency by ozonation, the pH values were adjusted to 5, 7, and 9 for CIP concentrations of 1, 5, and 10 mg/L, with contact times ranging from 0 to 60 min. As shown in Figure 5(a), at pH 5, the removal efficiencies for CIP concentrations at varied CIP concentrations of 1, 5, and 10 mg/L were 73.33%, 70.49%, and 49.77%, respectively. At pH 7, the removal efficiencies for the same concentrations increased to 76.73%, 74.59%,

and 65.63% (Figure 5b). At pH 9, the removal efficiencies were 80.03%, 77.12%, and 70.19%, respectively (Figure 5c). The results indicate that ozonation was more effective at lower CIP concentrations, achieving faster and more efficient removal. Higher CIP concentrations required more time and exhibited lower efficiency. At pH 7 and 9, removal efficiency increased rapidly, whereas at pH 5, the increase was more gradual. This trend can be attributed to the higher hydroxide ion concentration at pH 7 and 9, which enhances hydroxyl radical formation, leading to improved oxidation efficiency compared to acidic conditions.







(b) pH 7



(c) pH 9

Figure 5. CIP removal efficiencies by ozonation alone at different pHs (a) pH 5, (b) pH 7 and (c) pH 9

## *3.3 Effect of pH on CIP removal efficiency by catalytic ozonation*

The effect of pH on CIP removal efficiency by catalytic ozonation was evaluated using a CIP concentration of 5 mg/L, a catalyst dosage of 0.5 g/L, and a contact time of 0-60 minutes. As shown in Figure 6, with the catalyst, the removal efficiencies at pH 5, 7, and 9 after 60 minutes were within a similar range of 81.16% to 82.93%. In contrast, ozonation alone exhibited an increasing trend in removal efficiency as pH increased. This finding suggests that the catalyst primarily enhanced removal efficiency in the early stages of the reaction. At pH 7 and 9, removal efficiency remained comparable due to the high hydroxide ion concentration, which facilitates hydroxyl radical formation. However, at pH 5, the catalyst significantly improved removal by promoting hydroxyl radical generation, demonstrating its effectiveness under acidic conditions.

## 3.3.1 Effect of catalyst dosage on CIP removal efficiency by catalytic ozonation

The effect of catalyst dosage on CIP removal efficiency was evaluated at dosages of 0.2, 0.5, 0.7, and 1 g/L under pH conditions of 5, 7, and 9. The results showed that at pH 5, removal efficiencies with catalyst dosages of 0.2, 0.5, 0.7, and 1 g/L were 79.60%, 81.16%, 85.61%, and 80.27%, respectively, compared to 70.49% without the catalyst (Figure 7a).

At pH 7, efficiencies were 79.74%, 82.93%, 85.37%, and 80.58%, compared to 74.59% without the catalyst (Figure 7b). At pH 9, efficiencies were 84.51%, 81.56%, 81.99%, and 80.59%, compared to 77.12% without the catalyst (Figure 7c). The results indicate that the magnetite-supported alginate catalyst improved removal efficiency across all pH levels. The optimal catalyst dosages were 0.7 g/L at pH 5 and 7, and 0.2 g/L at pH 9. Using the optimal dosage enhanced CIP removal efficiency, with higher pH values further supporting the formation of hydroxyl radicals.

#### 3.3.2 Effect of initial CIP concentration on CIP removal efficiency by catalytic ozonation

The effect of initial CIP concentration on removal efficiency was investigated by varying CIP concentrations at 1, 5, and 10 mg/L at varied pH 5, 7, and 9. The results exhibited that removal efficiency was inversely related to the initial concentration, with lower concentrations allowing more effective interactions with oxidants. With all tested pH, the efficiency decreased as CIP concentration increased, due to the increased demand for ozone and hydroxyl radicals, as shown in Figure 8 (a)-(c).

From the results, the optimal conditions were identified in two scenarios based on pH. At pH 5 and 7, with an initial CIP concentration of 5 mg/L and a catalyst dosage of 0.7 g/L, removal efficiencies were



Figure 6. CIP removal efficiencies by catalytic ozonation compared with ozonation alone at different pHs [CIP conc. 5 mg/L, catalyst dosage 0.5 g/L]

85.61% and 85.37%, respectively, after 60 minutes, compared to 70.49% and 74.59% with ozonation alone. At pH 9, with the same initial CIP concentration but a reduced catalyst dosage of 0.2 g/L, removal efficiency reached 84.51%, while ozonation alone achieved 77.12%.

## 3.4 Study of the chemical kinetics of CIP removal reaction

The kinetics of CIP removal by catalytic ozonation was analyzed by plotting the linear relationship between CIP concentration and reaction time. A strong linear fit was





(c) pH 9

Figure 7. Effects of catalyst dosage on CIP removal efficiency at different pHs (a) pH 5, (b) pH 7, and (c) pH 9

observed, identifying reaction orders and rate constants (k). The experimental data confirmed that both ozonation alone and catalytic ozonation followed a second-order reaction model. Table 1 presents the kinetic analysis results under different conditions. The results revealed that catalytic ozonation significantly increased the reaction rate constant (k) compared to ozonation alone, demonstrating the ability of catalyst ability to enhance CIP removal. The reaction rate constant increased with higher pH, lower initial CIP concentrations, and optimal catalyst dosages., indicating that CIP concentration, pH, and catalyst presence directly influenced the reaction kinetics.

#### 3.5 Reusability of the catalyst

The reusability of the magnetite-supported alginate catalyst was evaluated by separating it from treated wastewater using a magnetic field and testing its efficiency over multiple cycles. Experiments were conducted with an initial CIP concentration of 5 mg/L, a catalyst dosage of 0.7 g/L, and a pH of 7. As shown in Figure 9, the catalyst exhibited similar removal efficiencies of 85.97%, 85.73%, 85.86%, 85.41%, and 85.51% over five cycles. These results indicate that the catalyst retains high efficiency even after multiple uses, demonstrating its stability, durability, and suitability for practical wastewater treatment applications.

Table 1. Reaction rate constants for the removal of ciprofloxacin under different conditions

No.	Catalyst (g/L)	рН	[CIP] – (mg/L)	Rate constant*		Position
				Ozone	Catalytic	order
				alone	Ozonation	
1	0.2	9	10	0.0040	0.0085	$2^{nd}$
2	0.2	9	5	0.0123	0.0216	$2^{nd}$
3	0.2	9	1	0.0686	0.1055	$2^{nd}$
4	0.7	7	10	0.0034	0.0055	$2^{nd}$
5	0.7	7	5	0.0105	0.0191	2 <sup>nd</sup>
6	0.7	7	1	0.0411	0.0801	$2^{nd}$
7	0.7	5	10	0.0015	0.0042	$2^{nd}$
8	0.7	5	5	0.0081	0.0198	$2^{nd}$
9	0.7	5	1	0.0401	0.0801	2 <sup>nd</sup>

\* Second-order reaction rate constant is measured in  $(mg/L)^{-1}$  minute<sup>-1</sup>







(b) pH7



(c) pH9

**Figure 8.** Effects of the initial CIP concentration on CIP removal efficiency by catalytic ozonation compared with ozonation alone at different pHs (a) pH 5, (b) pH 7 and (c) pH 9



Figure 9. Reusability potential of the catalyst

### 4. Conclusion

This research successfully synthesized a magnetite-supported alginate to use as a catalyst in catalytic ozonation for treatment of CIP in wastewater. FT-IR result exhibited the peaks corresponding to carboxyl (COO<sup>-</sup>) and O-Fe-O functional groups, indicating effective Fe<sub>3</sub>O<sub>4</sub> deposition on the alginate surface. The composite exhibited magnetic properties that enable catalyst recovery after use in wastewater treatment. The investigation of factors affecting CIP removal efficiency by catalytic ozonation demonstrated that removal efficiency varied with pH (5, 7, and 9) and catalyst dosage (0.2, 0.5, 0.7, and 1.0 g/L)while being inversely related to initial CIP concentrations (1, 5, and 10 mg/L). The catalytic ozonation promoted hydroxyl radical (·OH) generation, enhancing oxidation potential and significantly improving removal efficiency compared to ozonation alone. Optimal conditions were identified in two scenarios based on pH. At pH 5 and 7, with an initial CIP concentration of 5 mg/L and a catalyst dosage of 0.7 g/L, removal efficiencies were 85.61% and 85.37%, respectively, after 60 minutes, compared to 70.49% and 74.59% with ozonation alone. At pH 9, with the same initial CIP concentration but a reduced catalyst dosage of 0.2 g/L, removal efficiency reached 84.51%, while ozonation alone achieved 77.12%. Kinetic studies indicated that CIP removal via both catalytic ozonation and ozonation alone followed a second-order reaction model, with an increased rate

constant when the catalyst was used. This enhancement was attributed to the catalyst's ability to accelerate ozone decomposition and generate hydroxyl radical. Additionally, the magnetite-supported alginate catalyst exhibited effective reusability, maintaining performance for up to five cycles without significant efficiency loss. These findings highlight its environmental sustainability, cost-effectiveness, and potential for practical wastewater treatment applications.

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