1. Introduction

Catechol released from chemical, petrochemical, and pharmaceutical industrial wastes is ubiquitous in the environment [1, 2]. It is listed as a class B carcinogen by global health conventions, and therefore, its mitigation from the environment is a priority. Conventional wastewater treatment plants were never designed or did not completely remove non-biodegradable organic pollutants because of their persistence and resistance to biological attack and stability [3]. Treatment methods based on adsorption or membrane technology are inefficient to remediate organic pollutants because they merely concentrate them without destruction.

Advanced oxidation processes (AOP) based on $\cdot$OH radicals offer an attractive alternative for the complete mineralization of recalcitrant organic pollutants [4-7]. Classical Fenton and Fenton-like processes have been used over three decades [8], which operate in a narrow pH window with an inefficient use of $\text{H}_2\text{O}_2$. Irrespective of the presence of $\cdot$OH radicals, the oxidation of $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+} + e^-$ is rapid, which often results in sludge formation. However, the reduction process of $\text{Fe}^{3+}$ is comparably slow, and therefore, it determines the overall efficiency of the Fenton Process [9]. Also, high ferrous iron consumption and large sludge production in the conventional Fenton reaction [10]. Many variants to classical Fenton processes such as photo-, electrochemical- or sono- assisted Fenton-like processes have been proposed to overcome the limitations mentioned above with limited success [3, 11-15]. Some researchers attempted to convert $\text{H}_2\text{O}_2 \rightarrow \cdot\text{OH}$ directly for degradation of pollutants [16-18]. However, all of the above methods require additional energy or organic agents while the utilization rate of iron ions and the oxidation of the complexing agent are not satisfied.

In view of this, it is of great significance to find a new method of Fenton to improve the utilization efficiency of $\text{H}_2\text{O}_2$, accelerate
the reduction rate of trivalent iron ions, and increase the concentration of ferrous ions in the oxidation system. Herein, we propose a novel homogeneous system based on the classical Fenton process to overcome most of the limitations above. Compared with the classical Fenton process, the proposed system can operate in a wider pH window with high efficiency meanwhile minimizing contaminants in solution. The catechol was used as the model compound to assess the reaction efficiency. Cerium (IV) is selected as the electron shuttling due to its well-known redox cycling properties between Ce³⁺ and Ce⁴⁺ state. Ce⁴⁺ is a strong reductant at alkaline conditions, and Ce³⁺ is a strong oxidant under acidic environments [19-22]. The Ce³⁺/ Ce⁴⁺ redox cycling was used for the in situ production of Fe²⁺ to facilitate the Fenton process. Further, we characterized the resultant solution and the sludge using ICP-MS and XPS/FTIR, respectively.

2. Material and Methods

2.1. Materials
All chemicals used in this study were of analytical grade and used without further purification. Catechol (C₆H₄O₂), ferrous sulfate (FeSO₄·7H₂O), iron(III) chloride hexahydrate (FeCl₃·6H₂O), cerium(III) chloride heptahydrate (CeCl₃·7H₂O), hydrogen peroxide (H₂O₂, 30%), tert-butanol (C₆H₁₃O), sulfuric acid (H₂SO₄), and sodium hydroxide (NaOH) were purchased from Shanghai Chemical Reagent Co. Ltd, P. R. China. All sample pH adjustments were made either with 0.1M NaOH or 0.1M H₂SO₄. Ultrapure deionized water (conductivity ~18.25 MΩ•cm) was used for all sample preparations.

2.2. Experiment Methods
Typically, Fenton or Fenton-like reactions were conducted in a batch reactor using a 100 mL glass flask. Catechol was used as a model compound to evaluate the degradation efficiency of various reactors presently tested. For all degradation experiments, kept the volume of solution at 100 mL and the concentration of catechol at 10mM. The pH was adjusted using 0.1 M H₂SO₄ or 0.1 M NaOH. The batch solution was stirred throughout an experimental cycle at 200 rpm in the dark at 25°C. The degradation of catechol by classical Fenton and Fenton-like processes were compared. Effect of pH (3, 5, 7), Fe²⁺ concentration (0, 4 mM), Fe³⁺ concentration (0, 1, 2, 3, 4 mM), Ce³⁺ concentration (0, 1, 2, 3, 4 mM), H₂O₂ dosage (5, 8, 10, 20, 30 mM), reaction time (0, 2, 5, 8, 10, 20, 30, 60 min) were investigated. After each reaction time, 5 mL sample aliquots were syringe-filtered (0.22 μm membrane pore) into sampling tubes containing tert-butanol as OH scavenger and reserved them for chemical analysis. Each batch sequence experiment was repeated five times, and the average value was taken as the final value. UV and mass spectrometric methods analyzed the chemical composition of the treated water. Characterization of free radical products generated by our Fe³⁺-Ce³⁺-H₂O₂ and classical Fenton-like processes were characterized by ESR spectroscopy using DMPO as a spin trap. The sludge generated from the process was separated by filtration and centrifugation. The resultant solid substrate was oven-dried at 110°C, and processed for surface characterization by FTIR and XPS.

3. Results and Discussion

3.1. Influences of Experimental Conditions on the Degradation of Catechol

3.1.1. Effect of initial pH and different process
The effect of initial pH on the degradation of catechol by five different Fenton or Fenton-like processes was investigated with a different ratio of Fe²⁺, Fe³⁺ and Ce³⁺. Keeping the H₂O₂ concentration constant (20 mM), five different processes were selected including the Ce³⁺-H₂O₂ Fenton-like process, the classical Fenton process, the Fe³⁺-H₂O₂ Fenton-like process, the Fe³⁺-Ce³⁺-H₂O₂ Fenton-like process and the Fe³⁺-Ce³⁺-H₂O₂ Fenton-like process. The catechol degradation was monitored for each process at different pH = 3, 5, 7 respectively (Fig. 1). For the Ce³⁺-H₂O₂ Fenton-like process, the efficiency of catechol degradation increases with the pH and the highest degradation of catechol is observed around

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**Fig. 1.** Effect of pH on the catechol degradation by five different Fenton or Fenton like processes (Conc. H₂O₂ = 20 mM).
16.7% in pH 7 reactor. Also, we observed higher catechol degradation rate in classical Fenton process when compared to the Ce³⁺-H₂O₂ Fenton-like process. The addition of Ce³⁺ to classical Fenton or Fenton-like processes showed an increasing catalytic activity as pH grows from 3 to 7 where the efficiency of catechol degradation nearly doubled in the presence of Ce³⁺ at pH 7. Out of the reactors examined, the Fe³⁺-Ce³⁺-H₂O₂ process at pH shows the highest catechol degradation (~97%). This process not only improves catechol degradation but also broadens the operational pH window to environmentally compatible values. We suggested when the solution pH increased from 3 to 7, the catalytic role played by Ce³⁺ becomes significant. In neutral solutions, both classical Fenton and Ce³⁺-H₂O₂ Fenton-like processes produce •OH and O₂•⁻/O₂⁻ radicals, which can degrade the catechol [23].

3.1.2. Effect of Fe³⁺: Ce³⁺ ratio

The effect of Fe³⁺: Ce³⁺ ratio on catechol degradation by Ce³⁺-Fe³⁺-H₂O₂ Fenton-like process was examined as a function of Fe³⁺ and Ce³⁺ concentration. As shown in Fig. 2(a), with the Ce³⁺ concentration increased from 0 to 2 mM, the catechol degradation has steadily increased, and reaching an optimal at 2 mM. After that, the degradation efficiency remains stable with a further increase of Ce³⁺. Similarly, the catechol degradation by our Fenton-like process was also examined as a function of Fe³⁺ concentration, and the results are shown in Fig. 2b. With the increasing of Fe³⁺, the removal of catechol increased reaching a maximal catechol degradation at 4 mM Fe³⁺. Finally, we concluded Fe³⁺: Ce³⁺ = 2:1 optimal ratio for maximum catechol degradation (96.70% ± 0.12%). As can be seen, Ce³⁺ has a more significant effect than Fe³⁺. The reason for this is likely to be the introduction of Ce³⁺ reinforces the Fe³⁺/Fe²⁺ redox cycle, and the Fe²⁺ generated in situ can promote the Fenton process [24].

3.1.3. Effect of H₂O₂ concentration

Optimal H₂O₂ concentration required to maximize catechol degradation was also evaluated using Fe³⁺-Ce³⁺-H₂O₂ keeping Fe³⁺: Ce³⁺ = 2:1 ratio. The results thus obtained within 60 min. are shown in Fig. 3. The degradation of catechol by our process is increased with the H₂O₂ concentration reaching an optimal value at 20 mM. When H₂O₂ concentration increases further, the degradation efficiency shows a mild decline due to the •OH quenching process. The H₂O₂ concentration reaches a steady state after within the first 20 min (Fig. S1). Therefore, we concluded that a typical reaction cycle is essentially completed within 20 min.

3.1.4. COD and TOC removal capacity by cerium-iron-based Fenton-like process

In the reaction condition, Fe³⁺: Ce³⁺: H₂O₂ = 4:2:20 and pH = 7, TOC and COD in the solution before after the reaction were determined. The reaction results are shown in Fig. 4. The removal performance of both TOC and COD in iron cerium-based Fenton for removal of catechol in solution is excellent. With the removal of TOC reaching 97.3% and COD reaching 94.2%.
3.2. Reaction Mechanism and Degradation Path Analysis

3.2.1. Sediment characterization

FTIR and XPS spectroscopy characterizes the sludge created by our Fenton-like process. Fig. S2(b) shows the XPS survey scan showing the presence of Ce3d, O1s, C1s, and Fe2p peaks in the sludge sample. As in Fig. S2(b), the C1s band resolved into three peaks correspond to C-C (284.74 eV), C-O (286.3 eV), and C=O (288.55 eV) indicate catechol in solution. In agreement with IR data, the O1s band resolves as C-O (532.6 eV) and O-H (531.5 eV), which confirms the presence of water. It has been destroyed by the oxidation of the Fenton reaction and forms a precipitate under the action of coagulation precipitation. The Ce 3d band resolves into seven peaks (Fig. S2(d)). The peaks correspond to spin-orbital states 3d 5/2, and 3d 3/2 are labeled as V and U, respectively. The mixed oxidation states of cerium, viz. +3 and +4 are also present (901.2 eV and 882.5 eV) [25]. The interactions between the Ce3d orbitals result in rapid transitions between Ce3+ and Ce4+. Fig. S2(e) shows the XPS spectrum of Fe 2p. The binding energies of 711.3 eV and 714 eV belong to the Fe 2p3/2 orbitals, but the binding energy of 724.8 eV belongs to the Fe 2p1/2 orbital [26]. Our data confirm the presence of Fe 2+ and Fe3+ in the sludge.

We pay particular attention to determine sorbed catechol or other degraded products in the sludge. The IR bands marked in Figure S3 results due to trace degraded organic moieties. The characteristic broad IR band around 3300 – 2,500 cm⁻¹ is due to bending and stretching modes of water. However, the bands specific to catechol, viz. 3,375 cm⁻¹ due to phenolic -OH stretching, or 1,466 and 1,360 cm⁻¹ bands due to aromatic ring vibrations, are absent confirming its complete mineralization by our method.

3.2.2. Free radical generation mechanism

To identify possible free radical products of the Ce3+-Fe3+-H2O2 Fenton-like reaction, we used electron spin resonance (ESR) method with DMPO spin trap. ESR experiments were performed in optimized Ce3+-Fe3+-H2O2 and Fe3+-H2O2 Fenton-like processes. After five minutes, DMPO was added to scavenge •OH radical [27]. As shown in Fig. 5, four adsorption peaks correspond to •OH with an intensity 1:2:2:1 are observed in Fe3+-Ce3+-H2O2 Fenton-like process, while no evidence is found for the formation of •OH in Fe3+-H2O2 process. This result confirms that Ce3+ acts synergistically with Fe3+ for •OH production.

Based on the data so far presented, we devised a degradation mechanism of catechol by our Fe3+-Ce3+-H2O2 Fenton-like process, as illustrated in Fig. 6. The Fe3+ is transformed into Fe2+ through the Ce3+/ Ce4+ redox cycle. Afterward, the classical Fenton process is operative with H2O2 for the degradation of catechol into CO2 and H2O at neutral pH. To determine the most efficient radical out of •OH, and HO2•/•O2−, TBA and IPA were used as •OH quenchers, and chlorofoem was used as the HO2•/•O2− quencher [28] (Fig. S4). Our data confirm the efficiency of the •OH radical when compared to HO2•/•O2−, and the also take part in the Ce3+-Fe3+-H2O2 Fenton-like reaction.

Fig. 4. COD and TOC before and after the reaction (10 mM catechol, Fe3+:Ce3+:H2O2=4 mM : 2 mM : 20 mM)

Fig. 5. ESR spectra of the Fe3+-Ce3+-H2O2 Fenton-like process and Fe3+-H2O2 Fenton-like process.

Fig. 6. Ce3+-Fe3+-H2O2 homogeneous Fenton-like process schematic. (a) Generation of Activated radicals. (b) Degradation of organic compounds.
3.2.3. Analysis of catechol degradation pathway

The composition of the catechol solution before and after treatment with our Fenton-like process was determined by GC-MS. Fig. 7(a) is the raw water sample of untreated catechol, and Fig. 7(b) is the water sample after the reaction. The catechol fragments into a large number of small molecules. The catechol degradation pathway is multi-facet [29]. A possible degradation pathway is postulated based on mass spectral data in Fig. 8.

On the basis of previous discussion, the process for the enhanced Fenton-like processes of cerium can be described as follows [23]:

\[ \text{Ce}^{3+} + \bullet \text{OH} + \text{H}^+ \rightarrow \text{Ce}^{4+} + \text{H}_2\text{O} \quad (1) \]

\[ \text{Ce}^{3+} + \text{OOH}^\bullet + \text{H}^+ \rightarrow \text{Ce}^{4+} + \text{H}_2\text{O}_2 \quad (2) \]

\[ \text{Ce}^{4+} + \text{H}_2\text{O}_2 \rightarrow \text{Ce}^{3+} + \text{OOH}^\bullet \quad (3) \]

\[ \text{Ce}^{3+} + \text{OOH}^\bullet \rightarrow \text{Ce}^{3+} + \text{O}_2 + \text{H}^+ \quad (4) \]

\[ \text{Ce}^{3+} + \text{H}_2\text{O}_2 \rightarrow \text{Ce}^{4+} + \bullet \text{OH} + \text{HO}^- \quad (5) \]

\[ \text{Ce}^{4+} + \text{Fe}^{2+} \rightarrow \text{Ce}^{3+} + \text{Fe}^{3+} \quad (6) \]

As shown in reactions (1) to (5), the Ce$^{3+}$-H$_2$O$_2$ Fenton-like process triggers Ce$^{3+}$ $\Leftrightarrow$ Ce$^{4+}$ redox cycle, which also can quench \(\cdot\text{OH}\) and OOH$^\bullet$ radicals [30]. However, the complete elimination of \(\cdot\text{OH}\) by this process is not possible due to the reversibility of the reactions [30, 31]. When compared to \(\cdot\text{OH}\), OOH$^\bullet$ radical is a weak oxidant, and the production of OOH$^\bullet$ is larger than \(\cdot\text{OH}\) by Ce$^{3+}$/H$_2$O$_2$ at neutral pH [32]. OOH$^\bullet$ radical shows poor ability to degrade organic compounds [33]. Therefore, the standalone Ce$^{3+}$-H$_2$O$_2$ Fenton-like process results in inefficient degradation of catechol, particularly at acidic conditions.

Further, as shown in reaction (6), the Ce$^{4+}$ to Ce$^{3+}$ conversion is also thermodynamically feasible (Fe$^{3+}$/Fe$^{2+}$ 0.77 V; Ce$^{4+}$/Ce$^{3+}$ 1.44 V). Therefore, it appears that at acidic pH, the role of Ce$^{4+}$ in Fenton or Fenton-like processes are not significant. As solution pH increases, the catalytic role played by Ce$^{3+}$ becomes significant. In neutral solutions, dual-mode Fenton-like processes, namely classical Fenton and Ce$^{3+}$-H$_2$O$_2$ Fenton-like processes, seem active.

Fig. 7. Comparative GC-MS Diagram of Catechol solution (a) before and (b) after reaction.

Fig. 8. Schematic diagram of the reaction mechanism of the oxidation of catechol.
Herein, both processes produce •OH and OOH• radicals. The •OH radical is active for catechol degradation. Although OOH• is a weak radical for the degradation of catechol, it can readily convert Fe^{3+} \rightarrow Fe^{2+} by Ce^{3+} generating in situ Fe^{2+} for the Fenton process.

4. Conclusions

We have developed a homogeneous Fenton-like process using Fe^{3+}Ce^{3+}-H_{2}O_{2} to destruct organic pollutants efficiently. Our process operates in a wide pH range (3 to 7) with the highest efficiency for catechol degradation at pH 7. The Fe^{3+} required for the Fenton process is generated in situ, which minimizes •OH and Fe^{2+} recombination. Under the optimal conditions: pH = 7, Fe^{3+}:Ce^{3+}:H_{2}O_{2} = 4 mM: 2 mM: 20 mM, almost 97% of 10 mM catechol can be destructed. The wide operation pH window, minimal contaminants in solution, and high efficiency offer our Fenton-like process a promise in the advanced water treatment industry.

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Author Contributions

X.C. (Professor) contributed to the conception of the study and the data analyses, and revised the manuscript. X.L. (Ph.D. student) performed the experiment and wrote the manuscript. H.W. (M.S. student) performed the experiment and contributed significantly to manuscript preparation. K.C. (Professor) contributed to the data analyses with constructive discussions. R.W. (Professor) revised the manuscript. S.H. (Associate Professor) contributed to the data analyses with constructive discussions. G.L. (Engineer) contributed to the data analyses. J.P. (Engineer) contributed to the data analyses. K.Z. (Engineer) contributed to the data analyses. Electrico-Fenton Process and Related

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