Activation of peroxymonosulfate by metal (Fe, Mn, Cu and Ni) doping ordered mesoporous Co$_3$O$_4$ for the degradation of enrofloxacin

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Various transition metals (Fe, Mn, Cu and Ni) were doped into ordered mesoporous Co$_3$O$_4$ to synthesize Co$_2$O$_3$-composite spinels. Their formation was evidenced by transmission electronic microscopy (TEM), X-ray diffraction (XRD) and Brunauer–Emmett–Teller (BET) analysis. It was found that Co$_2$O$_3$-composite spinels could efficiently activate peroxymonosulfate (PMS) to remove enrofloxacin (ENR) and the catalytic activity followed the order Co$_3$O$_4$–CuCo$_2$O$_4$ > Co$_3$O$_4$–CoMn$_2$O$_4$ > Co$_3$O$_4$–CoFe$_2$O$_4$ > Co$_3$O$_4$–NiCo$_2$O$_4$. Moreover, through the calculation of the specific apparent rate constant ($k_{	ext{app}}$), it can be proved that the Co and Cu ions had the best synergistic effect for PMS activation. The Co$_2$O$_3$-composite spinels presented a wide pH range for the activation of PMS, but strong acidic and alkaline conditions were detrimental to ENR removal. Higher reaction temperature could promote the PMS activation process. Sulfate radical was identified as the dominating reactive species in Co$_2$O$_3$-composite spinel/ PMS systems through radical quenching experiments. Meanwhile, the probable mechanisms concerning Co$_2$O$_3$-composite spinel activated PMS were proposed.

1. Introduction

During the past years, sulfate radical (SO$_4$$^{2-}$) based advanced oxidation processes (SR-AOPs) have attracted an increasing interest among researchers owing to their great potential in degradation or even mineralization of recalcitrant organic pollutants.\(^1\) Compared with the hydroxyl radical (‘OH), SO$_4$$^{2-}$ possesses a longer lifespan, higher independence of pH and higher selectivity of oxidation.\(^2\) Peroxymonosulfate (PMS), a precursor of SO$_4$$^{2-}$, is deemed as a cost-effective and environmental-friendly oxidant.\(^3\) PMS remains stable in aqueous solution and barely decomposes into SO$_4$$^{2-}$ by itself, but it can be activated to produce SO$_4$$^{2-}$ by the use of UV, transition metals, and some nonmetal catalysts.\(^4\) Among different activation technologies, transition metals have attracted much attention due to their lower energy consumption and higher activation efficiency. Actually, many transition metal ions such as Co$^{2+}$, Mn$^{2+}$, Ni$^{2+}$, Fe$^{2+}$, Ru$^{3+}$, Ce$^{3+}$ and so forth, have been proved as qualified catalysts for PMS activation.\(^5\) Of note, Co$^{2+}$ has been found to possess the highest reactivity.\(^6\) Unfortunately, the Co$^{2+}$/PMS process is unfavorable in practical application because of the toxicity of Co$^{2+}$.

In order to relieve the secondary pollution, heterogeneous cobalt-based catalysts have become a research hotspot.

Anipsitakis et al. firstly employed Co$_3$O$_4$ to activate PMS and found Co$_3$O$_4$ presented an excellent catalytic behavior in the activation of PMS.\(^7\) Chen et al. successfully prepared nanoscale Co$_3$O$_4$ and tested its catalytic performance in PMS solution, results showed that 0.2 mM acid orange 7 (AO7) can be completely degraded within 30 min by 2 mM PMS in the presence of 0.5 g L$^{-1}$ Co$_3$O$_4$.\(^8\) Pu et al. fabricated three types of Co$_3$O$_4$ using different metal organic frameworks, and found that all the Co$_3$O$_4$ exhibited outstanding catalytic activity and the difference in catalytic ability can be attributed to the difference in specific surface area.\(^9\) Consequently, Co$_3$O$_4$/PMS system is quite acceptable from the viewpoint of application because of the high activation efficiency and limitation of cobalt leaching. However, on the basis of the underlying threat of cobalt ions, it is essential to take measures to further limit the cobalt leakage during PMS activation.

It is reported that bimetallic oxides may be desirable catalysts to ease the conflict between catalytic performance and metal ions leaching, because intimate interactions between two metals can effectively suppress the leakage of metal ions, such as Fe–Co interactions in CoFe$_2$O$_4$.\(^2\) Moreover, bimetallic oxides are also prominent PMS activators. Su et al. synthesized a series of Co$_x$Fe$_{3-x}$O$_4$ nanoparticles and found that the higher cobalt content in Co$_x$Fe$_{3-x}$O$_4$ showed the higher catalytic activity towards PMS.\(^10\) The high catalytic behavior of CoFe$_2$O$_4$ was also illustrated in our previous study.\(^11\) Yao et al. reported that CoMn$_2$O$_4$ showed stronger catalytic activity than Co$_3$O$_4$, Mn$_2$O$_3$, and their physical mixture due to the synergistic effects of Co
and Mn species. Similarly, CuCoO$_2$O$_4$ also exhibited high catalytic performance and low metal leachability in PMS solution. In our previous research, order mesoporous Co$_3$O$_4$ (OM-Co$_3$O$_4$) was fabricated and showed superior catalytic ability toward PMS than its spinel counterpart, but the leakage of cobalt was up to 77.74 µg L$^{-1}$ which was higher than conventional Co$_3$O$_4$ nanoparticles. Therefore, it can be reasonably speculated that cobalt leaching will reduce if some transition metals are doped to OM-Co$_3$O$_4$ to form mixed spinels with cobalt.

Herein, diverse transition metals (i.e., Fe, Mn, Cu and Ni) was introduced into OM-Co$_3$O$_4$ to synthesized a series of Co$_3$O$_4$-composite spinels which were characterized by transmission electronic microscope (TEM), X-ray diffraction (XRD), Brunauer–Emmett–Teller (BET) and Zeta potential analysis. Due to the ubiquitous detection in aquatic environment, enrofloxacin (ENR) was selected as target pollutant in this study. The catalytic activities of as-prepared Co$_3$O$_4$-composite spinels were systematically compared through apparent rate constant, PMS consumption, intensity of electron paramagnetic resonance (EPR) signal and specific apparent rate constant. Moreover, the effects of initial pH and reaction temperature during PMS activation were also investigated. Finally, a possible mechanism of PMS activation was proposed through quenching tests. To be best of our knowledge, it is the first time to apply order mesoporous Co$_3$O$_4$-composite spinels as effective PMS activators for the control of organic pollutants.

2. Materials and methods

2.1 Chemicals

ENR, acetonitrile (HPLC grade), Oxone (KHSO$_5$·0.5KH$_2$SO$_4$·0.5K$_2$SO$_4$, PMS, KHSO$_5$ $\geq$ 47%) and 5,5-dimethyl-1-pyrroline-N-oxide (DMPO) were obtained from Aladdin Biochemical Technology Co., Ltd. (Shanghai, China). The silica templates KIT-6 were purchased from Nanjing XFNANO Materials Tech Co., Ltd. (Jiangsu, China). Other chemical reagents were purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). Deionized water (18 MΩ cm) was produced from an Ulupure water purification system (Shanghai, China).

2.2 Catalysts preparation and characterization

OM-Co$_3$O$_4$ was synthesized using nanocasting route with KIT-6 as hard template, and the procedure was conducted as described before. For the preparation of Co$_3$O$_4$-composite spinels, 1.0 g OM-Co$_3$O$_4$ was dispersed in 2.5 mL ethanol of Fe(NO$_3$)$_3$, 9H$_2$O, Mn(NO$_3$)$_2$·2H$_2$O, Cu(NO$_3$)$_2$·3H$_2$O and Ni(NO$_3$)$_2$·6H$_2$O, respectively, and Co/M molar ratio was controlled at 3. After magnetic stirring for 1 h, the mixture was dried overnight at 60 °C and then calcined at 450 °C for 5 h (the heating rate was set at 2 °C min$^{-1}$). Finally, the obtained composite spinels were referenced Co$_3$O$_4$–CoM$_2$O$_4$ (M = Fe, Mn) and Co$_3$O$_4$–MCoO$_2$ (M = Cu, Ni) which depended on the oxidation state of dopant.

The crystal structures of catalysts were characterized by X’Pert PRO diffractometer (PANalytical, Holland) with Cu Kα radiation. The morphologies and structures of Co$_3$O$_4$– composite spinels were observed using transmission electron microscopy (TEM) (Philips, Holland). N$_2$ adsorption and desorption isotherms were measured using ASAP 2010 analyzer (Micromeritics, USA) at liquid nitrogen temperature (−196 °C). The pH at point of zero charge (pH$_{pzc}$) was determined by Zetasizer Nano analyzer (Malvern, UK).

2.3 Catalytic experimental procedure

The catalytic degradation experiments were performed with a 100 mL ENR solution at 10 mg L$^{-1}$ in 250 mL brown glass bottles, which were installed in a controlled temperature water bath stirring apparatus. In a typical run, specific amount of catalysts was added to ENR solution to receive adsorption–desorption equilibrium, followed by pH adjustment with H$_2$SO$_4$ and NaOH solution (100 mM) to ensure a desirable pH value after PMS addition. Subsequently, an appropriate amount of PMS was charged into the reaction solution to initiate experiment. At defined time intervals, 1 mL samples were collected and quenched with 0.1 mL Na$_2$SO$_4$ (100 mM). The resulting mixtures were immediately filtered by a 0.22 µm syringe filter for further analysis. All experiments were carried out in duplicates and the mean values were reported (with error bar).

2.4 Analytical methods

ENR concentrations were measured through a high-performance liquid chromatograph (HPLC, Agilent 1200, USA) with an Eclipse XDB-C18 column (5 μm particle, 150 × 4.5 mm), the concentrations were measured at λ = 278 nm using a mobile phase consisting of a mixture of acetonitrile and phosphoric acid (pH = 2.5) (v/v = 20 : 80) at a flow rate of 1.0 mL min$^{-1}$. The PMS concentrations were measured by the method of Waclawek et al. EPR analysis were performed on a Bruker A300 spectrometer (Germany) with DMPO as a spin-trapping agent. The parameters of EPR spectrometer were center field was 3360.67 G, sweep width was 100 G, static field was 3310.66 G, microwave frequency was 9.42 GHz, microwave power was 2.03 mW, modulation amplitude was 1.0 G and sweep time was 30.72 s.

3. Results and discussion

3.1 Characterization

The crystalline phases of OM-Co$_3$O$_4$ and Co$_3$O$_4$-composite spinels were displayed in Fig. 1. It was worth noting that the precursors and OM-Co$_3$O$_4$ would result in the formation of composite spinels at high temperature. The lattice of Co$_3$O$_4$ would host other cations through the replacement of cobalt cations. However, no significant difference can be observed between OM-Co$_3$O$_4$ and Co$_3$O$_4$-composite spinels in Fig. 1. The well-defined diffraction peaks of 2θ = 19.00°, 31.27°, 36.85°, 38.54°, 44.81°, 55.66°, 59.36° and 65.24° were corresponded to (111), (220), (311), (222), (400), (422), (511) and (440), respectively. This might be ascribed to that the unit cell parameters of CoFe$_2$O$_4$, CoMn$_2$O$_4$, CuCo$_2$O$_4$ and NiCo$_2$O$_4$ were very close to that of Co$_3$O$_4$. Thus these phases cannot be distinguished through XRD analysis. But according to Debye–Scherrer equation, the calculated mean crystallite sizes of OM-Co$_3$O$_4$, Co$_3$O$_4$–
CoFe$_2$O$_4$, Co$_3$O$_4$–CoMn$_2$O$_4$, Co$_3$O$_4$–CuCo$_2$O$_4$ and Co$_3$O$_4$–NiCo$_2$O$_4$ were 17.43, 25.32, 22.87, 27.35 and 24.86 nm, respectively. Compared with OM-Co$_3$O$_4$, the increase of mean crystallite sizes in Co$_3$O$_4$-composite spinels indicated that the introduction of metal dopants destroyed original structure of OM-Co$_3$O$_4$.

The TEM and HR-TEM images of OM-Co$_3$O$_4$ and Co$_3$O$_4$-composite spinels were showed in Fig. 2. It can be clearly seen that OM-Co$_3$O$_4$ showed a highly ordered mesoporous structure, and the spacing distances between two fringes are 0.285 and 0.467 nm, which were in conformity with (220) and (111) planes, respectively. Obviously, after the introduction of metal dopants, ordered mesoporous structure was partly or completely destroyed, which may be attributed to the formation of Co$_3$O$_4$-composite spinels. The lattice fringes can be clearly observed in HR-TEM images, indicating that highly crystalline nature of Co$_3$O$_4$-composite spinels, which was corresponded to the strong and sharp diffraction peaks in XRD analysis. Similarly with OM-Co$_3$O$_4$, the spacing distances between two fringes in Co$_3$O$_4$–CoFe$_2$O$_4$ were 0.281 and 0.471 nm, corresponding to (220) and (111) planes, respectively. And that in Co$_3$O$_4$–CoMn$_2$O$_4$ were 0.279 and 0.469 nm, which were also assigned to (220) and (111) planes, respectively. However, as for Co$_3$O$_4$–CuCo$_2$O$_4$ and Co$_3$O$_4$–NiCo$_2$O$_4$, the (111) plane was not observed, and the lattice spacing of 0.275 and 0.286 nm was corresponded to (220) plane.

The surface areas and pore size distributions of OM-Co$_3$O$_4$ and composite materials were investigated by N$_2$ adsorption–desorption isotherms. As shown in Fig. 3(a), all materials showed type IV isotherms, and the specific surface areas of OM-Co$_3$O$_4$, Co$_3$O$_4$–CoFe$_2$O$_4$, Co$_3$O$_4$–CoMn$_2$O$_4$, Co$_3$O$_4$–CuCo$_2$O$_4$ and Co$_3$O$_4$–NiCo$_2$O$_4$ were 66.91, 52.34, 50.92, 30.39 and 29.53 m$^2$ g$^{-1}$, respectively. The reduction of specific surface areas in Co$_3$O$_4$-composite spinels was ascribed to the deterioration of ordered mesoporous structure after the impregnation of metal cations, which was in accordance with the observation of TEM images. Moreover, compared with Co$_3$O$_4$–CoFe$_2$O$_4$ and Co$_3$O$_4$–CoMn$_2$O$_4$, the more significant decrease of specific surface areas in Co$_3$O$_4$–CuCo$_2$O$_4$ and Co$_3$O$_4$–NiCo$_2$O$_4$ may be related to the oxidation state of the doped metal ions. The formation of Co$_3$O$_4$–MCo$_2$O$_4$ consumed more Co$_3$O$_4$ than Co$_3$O$_4$–CoM$_2$O$_4$, thus the deterioration of ordered mesoporous structure in Co$_3$O$_4$–MCo$_2$O$_4$ was more significant than that of Co$_3$O$_4$–
CoM₂O₄, which can also be observed from TEM images. The changes of pore volume and pore diameter also demonstrated the conclusion, as seen in the Fig. 3(b), the pore volume and pore diameter all followed the order of OM-Co₃O₄ > Co₃O₄–CoM₂O₄ > Co₃O₄–MCo₂O₄. The textural parameters of OM-Co₃O₄ and Co₃O₄-composite spinels were summarized in Table 1.

XPS analysis can be used to determine the surface composition and chemical oxidation states of OM-Co₃O₄ and Co₃O₄-composite spinels. In XPS spectra of OM-Co₃O₄ (Fig. 4(a)), the sharp peak emerged at 779.6 eV was assignable to Co 2pₓ∕₂, which could be deconvoluted into octahedral Co³⁺ at 779.4 eV and tetrahedral Co²⁺ at 780.7 eV. The proportions of Co²⁺ and Co³⁺ were determined to be 63.01% and 36.99%, respectively. The O 1s envelope (Fig. 4(b)) could be deconvoluted into two parts, namely the lattice oxygen (Oₐₙ₅) at 529.2 eV and surface adsorbed oxygen (Oₐ₅₅₅₅) at 530.8 eV. Based on this deconvolution, the proportions of Oₐₙ₅ and Oₐ₅₅₅₅ were found to be 50.86% and 49.14%, respectively. Based on the doping of iron into OM-Co₃O₄, the content of Co²⁺ increased from 63.01% to 65.34%, which could be ascribed to the substitution of Co³⁺ with Fe³⁺ in OM-Co₃O₄. It was worth noting that the content of Oₐ₅₅₅₅ increased from 50.86% to 51.74%, which was conductive to the PMS activation.

As seen in Fig. 4(c), the doped iron existed in the form of positive trivalent.

3.2 Catalytic activity of Co₃O₄-composite spinels

ENR removal in different systems was presented in Fig. 5(a). Adsorption tests showed that all the catalysts exerted a low efficiency in ENR adsorption, and the highest efficiency was received by Co₃O₄–CoFe₂O₄ with 3.22% of ENR adsorption within 30 min, which may be attributed to the largest specific surface area. Although PMS is a strong oxidizing agent with oxidation potential of 1.82 V, only 16.36% ENR could be removed by PMS in the absence of activator. However, the ENR degradation was greatly enhanced in the presence of both Co₃O₄-composite spinels and PMS. ENR can be completely removed in Co₃O₄–CuCo₂O₄/PMS and Co₃O₄–CoMn₂O₄/PMS systems, and the removal efficiencies were 96.37% and 94.56%, respectively. Furthermore, the ENR degradation well followed a pseudo-first-order kinetics pattern:

\[
\ln \left( \frac{[\text{ENR}]}{[\text{ENR}]_0} \right) = -k_{\text{app}}t
\]

where [ENR]₀ is the initial ENR concentration, [ENR] is the concentration of ENR at time t, and \( k_{\text{app}} \) is the apparent rate constant. As seen in Fig. 4(b), the fitting \( k_{\text{app}} \) for Co₃O₄–CoFe₂O₄, Co₃O₄–CoMn₂O₄, Co₃O₄–CuCo₂O₄ and Co₃O₄–NiCo₂O₄ are 0.122, 0.255, 0.273 and 0.097 min⁻¹, respectively, which illustrated that the catalytic activity abided by the order of Co₃O₄–CuCo₂O₄ > Co₃O₄–CoMn₂O₄ > Co₃O₄–CoFe₂O₄ > Co₃O₄–NiCo₂O₄. In addition, Fig. 4(b) provided the PMS consumption during ENR oxidation. It can be seen that Co₃O₄–CuCo₂O₄ consumed the maximum PMS concentration (0.4 mM), which was 1.05, 1.74 and 2.00 times higher than Co₃O₄–CoMn₂O₄, Co₃O₄–CoFe₂O₄ and Co₃O₄–NiCo₂O₄, respectively. This result was also confirmed the sequence of catalytic activity of Co₃O₄-composite spinels.

EPR experiments were also performed for the comparison of the catalytic activity of Co₃O₄-composite spinels. As presented

![Fig. 3](a) Nitrogen adsorption–desorption isotherms of OM-Co₃O₄ and Co₃O₄-composite spinels and (b) their pore size distributions.

<table>
<thead>
<tr>
<th>Samples</th>
<th>XRD Crystallite size (nm)</th>
<th>N₂ adsorption–desorption Surface area (m² g⁻¹)</th>
<th>Pore volume (cm³ g⁻¹)</th>
<th>Pore diameter (nm)</th>
<th>pHₚzc</th>
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</thead>
<tbody>
<tr>
<td>OM-Co₃O₄</td>
<td>17.43</td>
<td>66.91</td>
<td>0.135</td>
<td>8.08</td>
<td>5.85</td>
</tr>
<tr>
<td>Co₃O₄–CoFe₂O₄</td>
<td>25.32</td>
<td>52.34</td>
<td>0.105</td>
<td>7.19</td>
<td>4.21</td>
</tr>
<tr>
<td>Co₃O₄–CoMn₂O₄</td>
<td>22.87</td>
<td>50.92</td>
<td>0.094</td>
<td>6.32</td>
<td>3.93</td>
</tr>
<tr>
<td>Co₃O₄–CuCo₂O₄</td>
<td>27.35</td>
<td>30.39</td>
<td>0.083</td>
<td>5.91</td>
<td>4.76</td>
</tr>
<tr>
<td>Co₃O₄–NiCo₂O₄</td>
<td>24.86</td>
<td>29.53</td>
<td>0.086</td>
<td>6.21</td>
<td>5.37</td>
</tr>
</tbody>
</table>
in EPR spectra (Fig. 5(c)), there was no distinctive EPR signal obtained by PMS alone. Nevertheless, simultaneous use of Co$_3$O$_4$-composite spinels and PMS could lead to obvious EPR signals. These EPR signals indicated the formation of 5,5-dimethyl-2-oxo-pyrroline-1-oxyl (DMPOX), which was ascribed to the fast activation of PMS and efficient oxidation of DMPOX, also proving the high catalytic performance of Co$_3$O$_4$-composite spinels. In addition, the signals of DMPOX caused by Co$_3$O$_4$–CuCo$_2$O$_4$/PMS and Co$_3$O$_4$–CoMn$_2$O$_4$/PMS systems were stronger than that caused by Co$_3$O$_4$–CoFe$_2$O$_4$ or Co$_3$O$_4$–NiCo$_2$O$_4$ activated PMS system (Fig. 5(b)), further authenticating the order of catalytic activity of Co$_3$O$_4$-composite spinels.

It was suggested that the catalytic performance of Co$_3$O$_4$-composite spinels not only depended on the specific surface area, but relied on dopant itself. In order to eliminate the difference in the specific surface area, the specific apparent rate constant $k_{\text{app}}$ which defined as the ratio of $k_{\text{app}}$ to the BET surface area was introduced:

$$k_{\text{app}} = \frac{k_{\text{app}}}{S_{\text{BET}}}$$

where $k_{\text{app}}$ is the specific apparent rate constant, and $S_{\text{BET}}$ is the specific surface area of composite spinels. As shown in Fig. 5(b), the $k_{\text{app}}$ of Co$_3$O$_4$–CuCo$_2$O$_4$ ($8.983 \times 10^{-3}$ g (m$^2$ min$^{-1}$)) was still the highest one which was 3.85, 1.79, 2.73 times higher than that of Co$_3$O$_4$–CoFe$_2$O$_4$, Co$_3$O$_4$–CoMn$_2$O$_4$ and Co$_3$O$_4$–NiCo$_2$O$_4$, respectively, indicating that Co and Cu ions possessed the best synergistic effect for PMS activation.

Fig. 4 XPS survey spectrum of Co 2p$_{3/2}$ (a), O 1s (b) and Fe 2p$_{3/2}$ (c) for OM-Co$_3$O$_4$ and Co$_3$O$_4$–CoFe$_2$O$_4$. 

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3.3 Effect of initial pH

The influence of initial pH ranging from 3 to 11 on ENR degradation was investigated in the PMS activation process, and the results were displayed in Fig. 6. From Fig. 6(a)–(e), it can be seen that four Co$_3$O$_4$-composite spinels all showed a wide pH range for PMS oxidation and higher ENR removals were obtained in pH range of 5 to 9 while lower removals occurred at strong acidic and alkaline conditions. Similar results were also reported by the previous investigations, such as degradation of orange II in MnFe$_2$O$_4$/PMS process and removal of acetaminophen in Fe$_3$O$_4$/PMS system.$^{25,26}$ The ENR degradation was significantly inhibited at strong acidic condition might be originated from the attachment of H$^+$ to the peroxide bond (O–O) of PMS (eqn (3)) and the change of catalyst surface charge (eqn (4)), so that the interfacial repulsion would result in a weaker catalytic performance.$^{27}$ The retardation of ENR removal at strong alkaline condition can be ascribed to the following reasons: (1) the increase of catalyst surface negative charges. The pH$_{pzc}$ of Co$_3$O$_4$–CoFe$_2$O$_4$, Co$_3$O$_4$–CoMn$_2$O$_4$, Co$_3$O$_4$–CoCo$_2$O$_4$ and Co$_3$O$_4$–NiCo$_2$O$_4$ was 4.21, 3.93, 4.76 and 5.37, respectively (Table 1). The surface charges of catalysts were negative when solution pH was higher than pH$_{pzc}$. Higher solution pH would cause higher amount of negative charges on catalyst surface, which could enhance the electrostatic repulsion between catalyst surface and PMS anions. Consequently, the catalytic performance decreased at strong alkaline condition. (2) The transform of dominant PMS species. Given that pK$_{a1}$ of H$_2$SO$_5$ was less than 0 and pK$_{a2}$ was 9.4, SO$_5^{2-}$/C$_0$ would replace HSO$_5^{-}$/C$_0$ and become dominant PMS species when solution pH was higher than 9.4. Compared with HSO$_5^{-}$ (E$_0$(HSO$_5^{-}$/SO$_4^{2-}$) = 1.75 V), SO$_5^{2-}$ (E$_0$(SO$_5^{2-}$/SO$_4^{2-}$) = 1.22 V) was less oxidative and more difficult to react.$^{28}$ Additionally, SO$_5^{2-}$ could also lead to a stronger electrostatic repulsion between catalyst surface and PMS anions.

$$\text{SO}_2 - \text{O} - \text{O} + \text{H}^+ \rightarrow \text{SO}_2 - \text{O} - \text{O} - \text{H}_2^+ \quad (3)$$
$$[\text{Cat} - \text{OH}] + \text{H}^+ \leftrightarrow [\text{Cat} - \text{OH}_2^+] \quad (4)$$

The values of $k_{\text{sapp}}$ were also calculated and the results were presented in Fig. 6(f). It could be more intuitionistic to compare the catalytic performances of four Co$_3$O$_4$-composite spinels in different conditions due to the elimination of difference in specific surface area. As shown in Fig. 5(f), Co$_3$O$_4$–CuCo$_2$O$_4$ maintained the highest $k_{\text{sapp}}$ values with pH varied from 3 to 11, suggesting that Co and Cu species were the best combination for PMS activation among these four spinels. However, it should be noted that the lowest $k_{\text{sapp}}$ value was showed by Co$_3$O$_4$–CoMn$_2$O$_4$ at pH 11 other than Co$_3$O$_4$–Fe$_2$O$_4$ or Co$_3$O$_4$–NiCo$_2$O$_4$. This might be closely related to pH$_{pzc}$ of catalysts, the
pH<sub>pcz</sub> of Co<sub>3</sub>O<sub>4</sub>–CoMn<sub>2</sub>O<sub>4</sub> was 3.93 which was much lower than that of other three Co<sub>3</sub>O<sub>4</sub>-composite spinels. It manifested that Co<sub>3</sub>O<sub>4</sub>–CoMn<sub>2</sub>O<sub>4</sub> could present lower performance at strong alkaline condition than others, thus Co<sub>3</sub>O<sub>4</sub>–CoMn<sub>2</sub>O<sub>4</sub> possessed the highest k<sub>sapp</sub> value.

3.4 Effect of temperature

The effect of reaction temperature (25, 35, 45 and 55 °C) on ENR removal in the process of PMS activation was studied. As displayed in Fig. 7(a–d), the ENR degradation in four Co<sub>3</sub>O<sub>4</sub>-composite spinels/PMS systems presented the similar trend, catalytic performances of Co<sub>3</sub>O<sub>4</sub>-composite spinels significantly increased with the increase of reaction temperature. As reaction temperature increased from 25 to 55 °C, k<sub>app</sub> values of Co<sub>3</sub>O<sub>4</sub>–CoFe<sub>2</sub>O<sub>4</sub>, Co<sub>3</sub>O<sub>4</sub>–CoMn<sub>2</sub>O<sub>4</sub>, Co<sub>3</sub>O<sub>4</sub>–CuCo<sub>2</sub>O<sub>4</sub> and Co<sub>3</sub>O<sub>4</sub>–NiCo<sub>2</sub>O<sub>4</sub> increased from 0.122, 0.255, 0.273, 0.097 min<sup>−1</sup> to 0.496, 0.872, 0.898, 0.498 min<sup>−1</sup>, respectively. This result may be due to the fact that higher reaction temperature simplified the rupture of O–O bond and generation of SO<sub>4</sub><sup>2−</sup> [29,30]. In addition, higher reaction temperature was beneficial for reactant molecules to overcome activation energy barrier [17]. The activation energy (E<sub>a</sub>) could be determined by plotting ln k<sub>app</sub> against 1/T based on Arrhenius equation (Fig. 7(e)). The obtained E<sub>a</sub> values were 40.73, 33.85, 33.07 and 45.51 kJ mol<sup>−1</sup> in Co<sub>3</sub>O<sub>4</sub>–CoFe<sub>2</sub>O<sub>4</sub>, Co<sub>3</sub>O<sub>4</sub>–CoMn<sub>2</sub>O<sub>4</sub>, Co<sub>3</sub>O<sub>4</sub>–CuCo<sub>2</sub>O<sub>4</sub> and Co<sub>3</sub>O<sub>4</sub>–NiCo<sub>2</sub>O<sub>4</sub> activated PMS systems, respectively. The lower E<sub>a</sub> value signified the higher catalytic reactivity, and the order of E<sub>a</sub> was well corresponded to the sequence of catalytic activity. Moreover, all the E<sub>a</sub> values were much higher than that of the diffusion-controlled reactions, which usually ranged from 10 to 13 kJ mol<sup>−1</sup> [31]. This implied that the apparent reaction rate for
ENR removal during Co$_3$O$_4$-composite spinels activated PMS processes was dominated by the rate of intrinsic chemical reactions on the catalyst surface. It was reported that out-sphere interactions were usually diffusion-controlled reactions, thus PMS activation by Co$_3$O$_4$-composite spinels was most likely an inner-sphere electron-transfer process. The consumption of PMS during ENR oxidation processes was monitored (Fig. 7(f)). Similar with the trend of $k_{app}$, PMS consumption also increased as the reaction temperature increased. The PMS consumption caused by Co$_3$O$_4$–CoFe$_2$O$_4$, Co$_3$O$_4$–CoMn$_2$O$_4$, Co$_3$O$_4$–CuCo$_2$O$_4$ and Co$_3$O$_4$–NiCo$_2$O$_4$ increased from 0.230, 0.372, 0.400 and 0.200 mM to 0.796, 0.954, 0.968 and 0.696 mM with the reaction temperature increased from 25 to 55 °C, suggesting that higher reaction temperature was conducive to PMS activation and ENR degradation, which was well corresponding to the conclusions by the observations of $k_{app}$ values. In addition, the higher PMS consumption also reflected higher catalytic reactivity. From Fig. 7(f), the PMS consumption caused by Co$_3$O$_4$-composite spinels always showed the sequence of Co$_3$O$_4$–CuCo$_2$O$_4$ > Co$_3$O$_4$–CoMn$_2$O$_4$ > Co$_3$O$_4$–CoFe$_2$O$_4$ > Co$_3$O$_4$–NiCuFe$_2$O$_4$ even in different reaction temperatures, indicating that Co$_3$O$_4$–CuCo$_2$O$_4$ possessed the highest catalytic activity among the four Co$_3$O$_4$-composite spinels.

3.5 Radical identification and catalytic mechanism

Three different scavengers, tert-butyl alcohol (TBA), ethanol (EtOH) and phenol were employed to identify the dominant radical species in Co$_3$O$_4$-composite spinels/PMS systems. TBA can rapidly react with $'OH$ ($k_{'OH} = 3.8-7.6 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$) but has a much lower reactivity with $'SO_4$ ($k_{'SO_4} = 4-9.1 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$), and EtOH is a well scavenger for $'OH$ and $'SO_4$ ($k_{'OH} = 1.2-2.8 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$, $k_{'SO_4} = 1.6-7.7 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$). Phenol
can also react with \( \cdot \text{OH} \) and \( \text{SO}_4^{2-} \) at a high rate \( (k_{\text{OH}} = 6.6 \times 10^3 \text{ M}^{-1} \text{ s}^{-1}, k_{\text{SO}_4^{2-}} = 8.8 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}) \). In view of the difference in reaction rates, using TBA, EtOH and phenol as scavengers was a feasible program for the identification of primary active species.

As presented in Fig. 8(a–d), only a slight reduction of ENR removal could be obtained in the presence of 10 or 100 mM TBA, implying that \( \cdot \text{OH} \) was involved in Co\(_3\)O\(_4\)–composite spinels activated PMS processes. With the addition of 10 mM EtOH, the ENR degradation was significantly inhibited and the removal efficiencies in Co\(_3\)O\(_4\)–CoFe\(_2\)O\(_4\), Co\(_3\)O\(_4\)–CoMn\(_2\)O\(_4\), Co\(_3\)O\(_4\)–CuCo\(_2\)O\(_4\) and Co\(_3\)O\(_4\)–NiCo\(_2\)O\(_4\) activated PMS processes were decreased from 97.37%, 100%, 100%, 94.56% to 66.84%, 69.92%, 82.42%, 57.81%, respectively. More addition of EtOH (100 mM) would cause further reduction of ENR removal efficiency with 47.90%, 47.70% 53.96% and 40.43%, respectively. The partial increase of Co\(_3^+\) was ascribed to the electrons donating of Co\(_2^+\) during the oxidation process. In the case of O 1s spectra (Fig. 4(b)), the content of O\(_{\text{lat}}\) decreased from 48.26% to 46.35%, and the proportion of O\(_{\text{ads}}\) increased from 51.74% to 53.65%. The increment of O\(_{\text{ads}}\) can be attributed to the generation of Co–OH or O\(_2\) adsorbed on the surface of Co\(_3\)O\(_4\)–CoFe\(_2\)O\(_4\). It has been reported that \( \equiv \text{Co}^{3+} – \cdot \text{OH} \) was the critical species for the generation of radicals during the process of PMS activation. Of note, the Fe 2p\(_{3/2}\) envelope could be deconvoluted into Fe\(_{2+}\) at 709.5 eV, which indicated that the redox reactions between Co and Fe were involved in the PMS activation.

Based on the results of quenching experiments and XPS analysis, the plausible mechanisms of Co\(_3\)O\(_4\)–composite spinels activated PMS were put forward. Taking Co\(_3\)O\(_4\)–CoFe\(_2\)O\(_4\)/PMS system as example, H\(_2\)O molecules were firstly physically absorbed on the part of \( \equiv \text{Co}^{2+} \) sites to generate \( \equiv \text{Co}^{2+} – \cdot \text{OH} \). Then, \( \equiv \text{Co}^{2+} – \cdot \text{OH} \) would react with HSO\(_5^-\) to form SO\(_4^{2-}\) (after introduction of PMS (eqn (5)), and could regenerate through the reaction between formed \( \equiv \text{Co}^{3+} – \cdot \text{OH} \) species and HSO\(_5^-\) (eqn (6)). Similarly, \( \equiv \text{Fe}^{3+} \) could also combine with dissociative adsorption of H\(_2\)O molecules to form \( \equiv \text{Fe}^{3+} – \cdot \text{OH} \), which would transform to \( \equiv \text{Fe}^{2+} – \cdot \text{OH} \) (eqn (7)) and generate \( \text{SO}_4^{2-} \) by reacting with HSO\(_5^-\) (eqn (8)). In addition, due to the standard redox potential of \( \equiv \text{Co}^{3+}/\equiv \text{Co}^{2+} \) was 1.92 V, while the standard redox potential of \( \equiv \text{Fe}^{3+}/\equiv \text{Fe}^{2+} \) was 0.77 V, the
reduction of \( \equiv \text{Co}^{3+} \) by \( \equiv \text{Fe}^{2+} \) was thermodynamically feasible (eqn (9)). The efficient regeneration of surface \( \equiv \text{Co}^{3+} \) by this process may be able to remain the stability and high efficiency of Co\(_3\)O\(_4\)-CoFe\(_2\)O\(_4\). Besides, \( \equiv \text{Co}^{3+} \) or \( \equiv \text{Fe}^{2+} \) on catalyst surface could also react with PMS to produce 'OH (eqn (10) and (11)), which could also be generate by the transformation of SO\(_4\)\(^{2-}\) (eqn (12) and (13)). Co\(_3\)O\(_4\)-CoMn\(_2\)O\(_4\), Co\(_3\)O\(_4\)-CuCo\(_2\)O\(_4\) and Co\(_3\)O\(_4\)-NiCo\(_2\)O\(_4\) activated PMS processes all presented the similar mechanism with Co\(_3\)O\(_4\)-CoFe\(_2\)O\(_4\) activated PMS process, and the reactions which were involved in Co\(_3\)O\(_4\)-composite spinels/PMS systems were listed in Table 2.

### 3.6 Reusability and stability of different Co\(_3\)O\(_4\)-composite spinels

The reusability of heterogeneous catalysts is an important indicator to assess the industrial application potential of heterogeneous catalysts. In this study, the reusability of different Co\(_3\)O\(_4\)-composite spinels was evaluated and the results were presented in Fig. 9(a). As shown, after being reused for three times, all the Co\(_3\)O\(_4\)-composite spinels still remained high catalytic activity toward PMS. Taking Co\(_3\)O\(_4\)-CoFe\(_2\)O\(_4\) as example, after three consecutive runs, just a slight reduction in ENR removal was observed and their values were 94.89%, 91.32% and 89.27%, respectively. The slight loss of catalytic activity was mainly ascribed to the leaching of metal ions during the consecutive runs. Therefore, the stability of different Co\(_3\)O\(_4\)-composite spinels was further investigated and the results were reported in Fig. 9(b). As exhibited, the leaching of cobalt was clearly observed after each run. With the increase of cycle times, the leaching concentration decreased. Of note, after doped different transition metals into OM-Co\(_3\)O\(_4\), the cobalt leakage can be effectively controlled, which was attributed to the intimate interactions between two metals. Therefore, Co\(_3\)O\(_4\)-composite spinels are ideal PMS activator for environmental remediation.

### Table 2  Reactions involved in composite spinels/PMS systems

<table>
<thead>
<tr>
<th>Systems</th>
<th>Reactions</th>
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<tbody>
<tr>
<td>Co(_3)O(_4)-CoFe(_2)O(_4)/PMS</td>
<td>( \equiv \text{Co}^{2+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Co}^{3+} - \text{OH} + \text{SO}_4^{2-} + \text{OH}^- ) (5)</td>
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<td></td>
<td>( \equiv \text{Co}^{3+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Co}^{3+} - \text{OH} + \text{SO}_4^{2-} + \text{H}^+ ) (6)</td>
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<td>( \equiv \text{Fe}^{2+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Fe}^{2+} - \text{OH} + \text{SO}_4^{2-} + \text{H}^+ ) (7)</td>
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<td>( \equiv \text{Fe}^{2+} + \equiv \text{Co}^{3+} \rightarrow \equiv \text{Fe}^{3+} + \equiv \text{Co}^{2+} ) (9)</td>
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<td></td>
<td>( \equiv \text{Co}^{2+} + \text{HOSO}_5^- \rightarrow \equiv \text{Co}^{3+} + \text{SO}_4^{2-} + \text{OH}^- ) (10)</td>
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<tr>
<td></td>
<td>( \equiv \text{Fe}^{2+} + \text{HOSO}_5^- \rightarrow \equiv \text{Fe}^{3+} + \text{SO}_4^{2-} + \text{OH}^- ) (11)</td>
</tr>
<tr>
<td>Co(_3)O(_4)-CoMn(_2)O(_4)/PMS</td>
<td>( \equiv \text{Co}^{2+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Co}^{3+} - \text{OH} + \text{SO}_4^{2-} + \text{OH}^- ) (12)</td>
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<td></td>
<td>( \equiv \text{Mn}^{3+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Mn}^{4+} - \text{OH} + \text{SO}_4^{2-} + \text{H}^+ )</td>
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<tr>
<td></td>
<td>( \equiv \text{Mn}^{3+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Mn}^{4+} - \text{OH} + \text{SO}_4^{2-} + \text{H}^+ )</td>
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<tr>
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<td>( \equiv \text{Co}^{2+} + \equiv \text{Mn}^{3+} \rightarrow \equiv \text{Co}^{2+} + \equiv \text{Mn}^{3+} )</td>
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<tr>
<td></td>
<td>( \equiv \text{Co}^{2+} + \equiv \text{Mn}^{3+} \rightarrow \equiv \text{Co}^{2+} + \equiv \text{Mn}^{3+} )</td>
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<td>( \equiv \text{Co}^{2+} + \equiv \text{Mn}^{3+} \rightarrow \equiv \text{Co}^{2+} + \equiv \text{Mn}^{3+} )</td>
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<tr>
<td>Co(_3)O(_4)-CuCo(_2)O(_4)/PMS</td>
<td>( \equiv \text{Co}^{2+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Co}^{3+} - \text{OH} + \text{SO}_4^{2-} + \text{OH}^- )</td>
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<td></td>
<td>( \equiv \text{Co}^{2+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Co}^{3+} - \text{OH} + \text{SO}_4^{2-} + \text{H}^+ )</td>
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<td>( \equiv \text{Cu}^{2+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Cu}^{2+} - \text{OH} + \text{SO}_4^{2-} + \text{OH}^- )</td>
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<td>( \equiv \text{Cu}^{2+} - \equiv \text{Co}^{2+} \rightarrow \equiv \text{Cu}^{3+} + \equiv \text{Co}^{2+} )</td>
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<td>( \equiv \text{Cu}^{2+} + \text{HOSO}_5^- \rightarrow \equiv \text{Cu}^{3+} + \equiv \text{SO}_4^{2-} + \equiv \text{OH}^- )</td>
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<tr>
<td>Co(_3)O(_4)-NiCo(_2)O(_4)/PMS</td>
<td>( \equiv \text{Co}^{2+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Co}^{3+} - \text{OH} + \text{SO}_4^{2-} + \text{OH}^- )</td>
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<tr>
<td></td>
<td>( \equiv \text{Co}^{3+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Co}^{3+} - \text{OH} + \text{SO}_4^{2-} + \text{H}^+ )</td>
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<td>( \equiv \text{Ni}^{3+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Ni}^{3+} - \text{OH} + \text{SO}_4^{2-} + \text{OH}^- )</td>
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<td>( \equiv \text{Ni}^{3+} - \text{OH} + \text{HOSO}_5^- \rightarrow \equiv \text{Ni}^{3+} - \text{OH} + \text{SO}_4^{2-} + \text{H}^+ )</td>
</tr>
<tr>
<td></td>
<td>( \equiv \text{Co}^{2+} + \equiv \text{HOSO}_5^- \rightarrow \equiv \text{Co}^{3+} + \equiv \text{SO}_4^{2-} + \equiv \text{OH}^- )</td>
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<tr>
<td></td>
<td>( \equiv \text{Ni}^{3+} + \equiv \text{HOSO}_5^- \rightarrow \equiv \text{Ni}^{3+} + \equiv \text{SO}_4^{2-} + \equiv \text{OH}^- )</td>
</tr>
<tr>
<td></td>
<td>( \equiv \text{SO}_4^{2-} + \equiv \text{H}_2\text{O} \rightarrow \equiv \text{HOSO}_4^- + \equiv \text{OH}^- )</td>
</tr>
<tr>
<td></td>
<td>( \equiv \text{SO}_4^{2-} + \equiv \text{OH} \rightarrow \equiv \text{SO}_3^{2-} + \equiv \text{OH}^- )</td>
</tr>
</tbody>
</table>
4. Conclusion

Co$_3$O$_4$-composite spinels were successfully synthesized through doping transition metals (Fe, Mn, Cu and Ni) to ordered mesoporous Co$_3$O$_4$. The obtained Co$_3$O$_4$-composite spinels all showed outstanding catalytic activity toward PMS. Co$_3$O$_4$–CuCo$_2$O$_4$ exhibited the highest catalytic performance in PMS solution, followed by Co$_3$O$_4$–CoMn$_2$O$_4$, Co$_3$O$_4$–CoFe$_2$O$_4$ and Co$_3$O$_4$–NiCo$_2$O$_4$. ENR degradation would be retarded in strong acidic and alkaline conditions, the improvement of reaction temperature could significantly accelerate ENR decomposition. Sulfate radical was confirmed to be the primary reactive species in Co$_3$O$_4$-composite spinels activated PMS processes and hydroxyl radical was also involved in these processes. The synergistic effect between two metals in Co$_3$O$_4$-composite spinels was the vital reason for the high catalytic reactivity. Co$_3$O$_4$-composite spinels displayed satisfactory reusability and doping different transition metals into OM-Co$_3$O$_4$ can effectively control the cobalt leaching. In consideration of cost and toxicity, Co$_3$O$_4$-composite spinels might have great potential in pollution control than OM-Co$_3$O$_4$.

Conflicts of interest

No conflict of interest exists in the submission of this manuscript and manuscript is approved by all authors for publication.

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