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Article

Novel-structured Mo-Cu-Fe-O composite for catalytic air oxidation of dye-containing wastewater under ambient temperature and pressure

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ABSTRACT

A novel-structured Mo-Cu-Fe-O composite was successfully prepared by co-precipitation and impregnation method. The properties of the as-prepared samples were determined using X-ray diffraction, temperature-programmed reduction by H_2 , cyclic voltammetry, and temperature-programmed desorption by O_2 . The results showed that Mo^{6+} diffused into the Cu-Fe-O crystal lattice and then formed a new crystalline phase of $CuMoO_4$. The Mo-Cu-Fe-O catalyst had redox properties, and its surface contained active sites for oxygen adsorption. In addition, the catalytic activity of the Mo-Cu-Fe-O composite was evaluated by the degradation of Cationic Red GTL, Crystal Violet, and Acid Red in catalytic wet air oxidation (CWAO) at ambient temperature and pressure. The Mo-Cu-Fe-O catalyst showed excellent activity at basic conditions for the degradation of Cationic Red GTL. High removal efficiencies of 91.5% and 92.8% were achieved for Cationic Red GTL and Crystal Violet, respectively, in wastewater, and the efficiency remained high after seven cycles. However, almost no degradation of Acid Red occurred in the CWAO process. Furthermore, hydroxyl radicals were formed in the CWAO process, which induced the decomposition of the two cationic dyes in wastewater, and the toxicity of their effluents was decreased after degradation. The results indicate that the Mo-Cu-Fe-O composite shows excellent catalytic activity for the treatment of wastewater contaminated with cationic dyes.

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1. Introduction

Dye-contaminated wastewater, released mainly by the textile industry and finishing processes, has received much attention [1]. Dyes are compounds of synthetic origin with complex aromatic molecular structures. During manufacturing and textile printing, the dyes are not always entirely consumed, and some may be released into the environment, causing coloration

of wastewater [2–4]. In some industries, the discharge of wastewater under uncontrolled and unsuitable conditions is causing significant environmental problems. Dye-containing wastewater can pose both direct and indirect threats to human health and ecological systems [5]. The control and treatment of dye-containing wastewater will undoubtedly be a key factor in human–environment interaction in the future [6,7]. Advanced oxidation processes (AOPs) have been widely proposed for

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elimination of dye from wastewater, particularly in low-concentrated effluents [5,8–11,12]. Several technologies, including the Fenton reaction, photo-Fenton, wet air oxidation (WAO), ozonation, and photocatalysis, are included among the AOPs. The difference among these AOP technologies is in the generation of the active oxidative species. For example, hydroxyl radicals ($\bullet\text{OH}$) play the central role in the WAO process [12,13]. WAO is one of the most economically and technologically viable AOPs for wastewater treatment [14,15]. In addition to its economic benefits, WAO is eco-friendly, in marked contrast to other AOPs using harmful (and expensive) oxidizing agents like ozone and hydrogen peroxide. Typical conditions for WAO are temperatures of 150–320 °C, pressures of 2–15 MPa, and residence times of 15–120 min; the preferred chemical oxidation demand (COD) load ranges from 10000 to 80000 mg/dm³ [16,17]. The operating costs are almost entirely incurred by the use of power to compress air and perform high-pressure liquid pumping. Adding a catalyst can enable the same or better oxidation efficiency at lower reaction temperatures and pressures, so reducing the operating costs.

The development of appropriate catalysts for the WAO process, i.e., catalytic wet air oxidation (CWAO), is an active area of research [18,19]. CWAO allows the use of less severe reaction conditions. In addition, it is suited to the decomposition even of refractory pollutants, thereby reducing capital and operating costs [20–22]. With the ability to exploit the high reactivity of hydroxyl radicals to drive oxidation, CWAO has emerged as a promising technology for the treatment of dye-containing wastewater [23,24]. In this context, attention has focused on the use of heterogeneous catalysts, which have excellent catalytic activity in CWAO under mild conditions [7,25,26]. Heterogeneous catalysts containing small amounts of Mo, such as nanoparticles, molybdenum oxides, and clay-immobilized molybdenum, have attracted considerable attention because of their wide structural variety and specific properties including nano-sized dimensions, surface charges, and surface activity [27,28]. The CuO-MoO₃-P₂O₅ mixed oxide was confirmed to be an active heterogeneous catalyst in the CWAO of methylene blue, achieving a color removal efficiency of 99.26% within 30 min at 35 °C and atmospheric pressure [25]. Excellent catalytic activity was also reported for the nanotubular polyoxomolybdate Zn_{1.5}PMo₁₂O₄₀ for the CWAO of Safranin-T, in which 98% of color and 95% of COD were removed within 40 min at room temperature and atmospheric pressure [23]. In another study, the CWAO process achieved almost complete removal of the color and COD of Safranin-T over the nanotubular catalysts ZnO/MoO₃ and MoO₃:Ce under ambient conditions. The dye Cationic Red GTL can be degraded by the CWAO process over the catalyst Mo-Zn-Al-O under ambient conditions, with a decolorization of 80.1%, and the process remains stable after multiple cycling runs [27]. Although a wide variety of metal oxides have now been reported for use in wet oxidation, the search for more active, stable heterogeneous catalysts is ongoing. In the Mo-Zn-Al-O catalyst, the active component is Mo and the carrier is Zn-Al layered double hydroxide (LDH). Cu-Fe-LDH is a catalytic material, and it was envisaged that the combination of Cu-Fe-LDH and Mo would improve the catalytic

activity and stability of the former. Moreover, since limited information is available on the degradation of differently-charged dyes in wastewater by CWAO, further research is needed.

In this study, Cationic Red GTL and Crystal Violet were selected as cationic dye models. Acid Red was chosen as a representative anionic dye model. The primary aim was to investigate the structure of the Mo-Cu-Fe-O catalyst and its catalytic activity for the degradation of those three dyes at room temperature and atmospheric pressure. The secondary aim was to explore the possible mechanism of CWAO at room temperature and atmospheric pressure through determining the active radical species involved.

2. Experimental

2.1. Materials

Cationic Red GTL, Crystal Violet, and Acid Red were purchased from Shanghai Luoqing Dyeing Chemical Co., Ltd. (China). The reagents for this study, including Cu(NO₃)₂·6H₂O (99%), Fe(NO₃)₃·9H₂O (99%), NaNO₃ (99%), NaOH (99%), H₂SO₄ (98%), and HCl (37%), were purchased from Sinopharm Chemical Reagent Co. Ltd.

2.2. Preparation of the Mo-Cu-Fe-O catalyst

The Mo-Cu-Fe-O catalyst was prepared by co-precipitation and impregnation method. A Cu-Fe-O precursor with a Cu:Fe molar ratio of 2:1 was prepared by direct co-precipitation at pH = 9.5 of a mixed aqueous solution of Cu(NO₃)₂·6H₂O and Fe(NO₃)₃·9H₂O, with the addition of NaOH [29]. The resulting suspension was kept at 80 °C with further stirring for 18 h. The resulting solid was filtered, washed several times with distilled water, dried at 100 °C for 18 h, and calcined at 400 °C. Hereafter, this sample is referred to as the Cu-Fe-O precursor. The Mo-Cu-Fe-O catalyst was prepared by impregnation. In that process, 20 g Cu-Fe-O precursor was impregnated in aqueous solution containing 100 mL 2 mol/L (NH₄)₆Mo₇O₁₆ at 55 °C with stirring for 12 h. Then, it was filtered and washed thoroughly with deionized water several times. After that, the resulting product was calcined at 400 °C for 1 h and cooled to room temperature; the resulting solid was denoted the Mo-Cu-Fe-O catalyst.

2.3. Characterization of the catalyst

Powder X-ray diffraction (XRD) patterns of the Mo-Cu-Fe-O catalyst and Cu-Fe-O carrier were recorded on a D/MAX-RB X-ray diffractometer (D/MAX-RB, Japan) using nickel-filtered Cu K α radiation (λ = 0.15418 nm) with a graphite monochromator at 40 kV and 120 mA. The patterns were recorded over a range of 2 θ angles from 10° to 90° and the crystalline phases were identified using the Joint Committee on Powder Diffraction Standards (JCPDS) files [30]. The zeta potential of the Mo-Cu-Fe-O catalyst was measured with a zeta meter (Malvern Nano-ZS90).

The temperature-programmed reduction of H_2 (H_2 -TPR) was performed on a Micromeritics Chemisorb 2720. The H_2 -TPR profile was obtained by passing a 5% H_2/He flow (50 mL/min) through the pretreated catalyst (about 50 mg). The temperature was increased from 25 to 800 °C at a rate of 10 °C/min. The hydrogen concentration was continuously monitored by a thermoconductivity detector. Prior to each H_2 -TPR test, the catalyst was pre-heated in a 5% O_2/He flow from 25 to 500 °C and then held for 30 min. After cooling to room temperature, pure He was fed to the reactor at 50 mL/min for 1 h to purge any residual O_2 [31]. The apparatus for temperature-programmed desorption of O_2 (O_2 -TPD) resembled that of H_2 -TPR in that the O_2 concentration in the effluent was continuously monitored by a TCD. Cyclic voltammetry (CV) of the samples was carried out in a three-electrode cell system using 1 mol/L KOH aqueous solution as the electrolyte with a CHI 760E electro-chemical workstation. Electron spin resonance (ESR) signal of radicals was obtained on a Bruker ESR 300 E spectrometer with an irradiation source of this instrument of Quanta-Ray Nd:YAG pulsed laser system. The reagent for spin-trapping $\bullet OH$ was 5,5-dimethyl-1-pyrroline-*N*-oxide [27].

2.4. Catalytic oxidation procedure

Catalytic reduction of dye-containing wastewater was carried out in a semi-batch reactor. The reactions were conducted at room temperature and atmospheric pressure. In a typical run, the reactor was filled with 0.1 L of 100 mg/L dye-containing wastewater and purged with air at an aeration rate of 400 mL/min for 60 min. The reaction started with the addition of 1.0 g/L Mo-Cu-Fe-O catalyst. During the catalytic oxidation procedure, the decolorization percentages of Cationic Red GTL, Crystal Violet, and Acid Red were estimated on the basis of the absorbency measured by an Ultraviolet-visible (UV-Vis) spectrophotometer. For comparison purposes, we also investigated the adsorption capacity of the Mo-Cu-Fe-O catalyst and the intrinsic catalytic activity of the Cu-Fe-O carrier. Under otherwise the same CWAO process, the gas in the adsorption experiment was N_2 . After the reaction, the suspensions were centrifuged and the Mo-Cu-Fe-O catalyst was decanted.

2.5. Toxicity of effluent

Chlorella vulgaris (FACHB-6) was obtained from the Freshwater Algae Culture Collection of the Institute of Hydrobiology, Chinese Academy of Sciences. *C. vulgaris* was illuminated at a light intensity of 2500 lx with a fluorescent lamp for a 14 h light/10 h dark regime at 25 ± 1 °C and cultured in OECD (Organization for Economic Cooperation and Development, 2006) medium with pH adjusted to 8.0 by NaOH or HCl. Cationic Red GTL and its degradation effluent were added to the culture media in separate trials. The EC_{50} value of Cationic Red GTL (the concentration causing a 50% inhibition of growth) was calculated at the 95% confidence limit using probity analysis [32]. The EC_{50} value of the effluent was found to vary with the concentration of Cationic Red GTL.

Fig. 1. XRD patterns of Mo-Cu-Fe-O catalyst and Cu-Fe-O precursor.

3. Results and discussion

3.1. XRD patterns of Mo-Cu-Fe-O catalyst

To identify the structural changes of the catalyst after calcination, the final catalyst and the uncalcined carrier (Cu-Fe-O precursor) were both characterized by XRD. The results are shown in Fig. 1. The XRD pattern of CuO with a cubic fluorite structure (JCPDS 65-2309) was dominant, as evidenced by the characteristic diffraction peaks from the (-111) and (111) planes at $2\theta = 36^\circ$ and 39° . Of particular interest is that there were no characteristic diffraction peaks of iron oxide. For Mo-Cu-Fe-O catalyst after calcination, the main characteristic diffraction peaks are at 2θ values of 24° , 26° , and 33° , which were attributed to $CuMoO_4$ (JCPDS 22-0242). It was evident that when the Cu-Fe-O precursor was doped with Mo, Mo^{6+} ions diffused into the crystal lattice and altered the phase composition of Cu-Fe-O, forming a new crystalline phase of $CuMoO_4$.

3.2. H_2 -TPR analysis of Mo-Cu-Fe-O catalyst

As seen in Fig. 2, the H_2 -TPR profile of the Mo-Cu-Fe-O catalyst provided useful information about its reducibility. Three sharp peaks were observed at 347, 415, and 536 °C. With respect to our previous Mo-Zn-Al-O catalyst [27], the peak at 347 °C in the Mo-Cu-Fe-O catalyst was new and was attributed to

Fig. 2. H_2 -TPR profile of Mo-Cu-Fe-O catalyst.

the reduction of Cu^{2+} to Cu^+ . The other two peaks were ascribed to the reduction of Fe^{3+} to Fe^{2+} . The one high-temperature peak, located at 536 °C, can be attributed to the reduction of Mo^{6+} to Mo^{5+} [33]. These two peaks were shifted to markedly lower temperatures compared with the Mo-Zn-Al-O catalyst, indicating that Cu and Fe might have facilitated the reduction of Mo [27]. The redox properties of this catalyst, with Mo exhibiting considerable reducibility, suggested the capacity for high catalytic performance. In order to study the redox potentials of the Mo-Cu-Fe-O catalyst, CV experiments were carefully performed over a range of scanning rates from 0.02 to 0.1 V/s. The reduction and oxidation of Cu^{2+} at 0.32 V can be observed in the CV curves measured at various scanning rates for the Mo-Cu-Fe-O catalyst (Fig. 3).

3.3. O_2 -TPD analysis of Mo-Cu-Fe-O catalyst

The O_2 -TPD curve of the Mo-Cu-Fe-O catalyst provided useful information about active oxygen adsorption sites [13]. There was one broad peak at 780 °C, confirming the presence of active adsorption sites in the Mo-Cu-Fe-O catalyst (Fig. 4). These were expected to endow the Mo-Cu-Fe-O catalyst with excellent catalytic activity, since catalytic activity is closely correlated with the presence of surface active oxygen.

3.4. Catalytic activity in the degradation of dye-containing wastewater

The catalytic activities of the Mo-Cu-Fe-O catalyst in the degradation of Cationic Red GTL, Crystal Violet, and Acid Red under ambient conditions in the CWAO process were investigated. As shown in Fig. 5, the maximum absorption wavelengths for Cationic Red GTL, Crystal Violet, and Acid Red were 490, 590, and 506 nm, respectively. For wastewater containing Cationic Red GTL and Crystal Violet dyes, the Mo-Cu-Fe-O catalyst exhibited excellent catalytic activity in the CWAO process. After 60 min, the removal efficiencies of Cationic Red GTL and Crystal Violet were 91.5% and 92.8%, respectively, under ambient conditions. However, Acid Red was barely degraded in this CWAO process. It is generally considered that physical

Fig. 3. CV profiles of Mo-Cu-Fe-O catalyst with different scan rates. (a) 0.1 V/s; (b) 0.05 V/s; (c) 0.02 V/s.

Fig. 4. O_2 -TPD profile of Mo-Cu-Fe-O catalyst.

adsorption must occur before any chemical reaction can proceed on the surface of a catalyst. Here, the essential initial step was the adsorption of the dye on the inner surface of the catalyst through capillary diffusion. The zeta potential of the Mo-Cu-Fe-O catalyst was -14.5 mV, easily allowing it to adsorb cationic dyes such as Cationic Red GTL and Crystal Violet. In contrast, the negative zeta potential of the Mo-Cu-Fe-O catalyst effectively prevented the degradation of Acid Red under ambient conditions, in the sense that only minimal adsorption of the dye occurred on the catalyst surface during the CWAO process.

To confirm the catalytic contribution of the Mo-Cu-Fe-O catalyst, the CWAO of Cationic Red GTL over the bare Cu-Fe carrier was compared with that in the presence of the Mo-Cu-Fe-O catalyst. Without catalyst, but with air bubbling, the decolorization efficiency was zero after 60 min (data not shown). This suggests that the oxidation of Cationic Red GTL by air alone is very limited under ambient conditions. As shown in Fig. 6, the decolorization of Cationic Red GTL (100 mg/L) was 90.4% over the Mo-Cu-Fe-O catalyst (1 g/L). This is higher catalytic activity than that of the Mo-Zn-Al-O catalyst, which, at a loading of 2.72 g/L, achieved 80.1% decolorization of Cationic Red GTL (at a dye concentration of 85 mg/L) [27]. In contrast, the Cu-Fe-O

Fig. 5. UV-vis spectra of dye-containing wastewater over Mo-Cu-Fe-O catalyst in CWAO process.

Fig. 6. Decolorization of wastewater containing Cationic Red GTL with Mo-Cu-Fe-O catalyst under air aeration and without air aeration in CWAO process.

carrier achieved a decolorization of only 7.8%. These results indicate that lattice arrangement of Mo^{6+} ions is the active component in the Mo-Cu-Fe-O catalyst and influences the entire reaction system. To investigate the adsorption ability of the Mo-Cu-Fe-O catalyst, tests of the catalytic degradation of Cationic Red GTL were carried out under both air aeration and N_2 aeration. With N_2 , the decolorization efficiency of Cationic Red GTL by the Mo-Cu-Fe-O catalyst was 32.0%, indicating that the Mo-Cu-Fe-O catalyst achieved positive adsorption of the Cationic Red GTL. More importantly, the decolorization over the Mo-Cu-Fe-O catalyst under air aeration was considerably higher than that under N_2 aeration. Based on these observations, it is logical to conclude that following the adsorption of Cationic Red GTL on the inner surface of the Mo-Cu-Fe-O catalyst through capillary diffusion, the chemical reaction of the dye and desorption of the degradation products also occurred on the inner surface of the catalyst.

The removal of Cationic Red GTL by CWAO with the Mo-Cu-Fe-O catalyst was investigated at pH 4, 6, 7, 8, and 10. The results are shown in Fig. 7. The catalytic activity of Mo-Cu-Fe-O was excellent at all pH conditions, thus showing applicability across a wider pH range than the Mo-Zn-Al-O catalyst [28]. The catalytic activity of the Mo-Cu-Fe-O catalyst was

Fig. 7. Decolorization of Cationic Red GTL at different pH values.

Fig. 8. Recycling runs in decolorization of Cationic Red GTL.

enhanced by about 10% as the pH increased from 4 to 10, indicating that it is more active under basic than acidic conditions.

3.5. Stability test of the Mo-Cu-Fe-O catalyst

The regeneration of the Mo-Cu-Fe-O composite catalyst in the CWAO process is of practical and economic importance. In this experiment, the suspension was centrifuged and the Mo-Cu-Fe-O catalyst was decanted after the reaction. The catalyst was not washed with deionized water but was directly dried at 110 °C. The recyclability of the Mo-Cu-Fe-O catalyst was evaluated by performing Cationic Red GTL degradation under the standard reaction conditions. As depicted in Fig. 8, the activity of the catalyst in the degradation of Cationic Red GTL decreased slightly during the first seven cycles because of the leaching of metal from the catalyst. Nonetheless, after seven experimental cycles, it still achieved 88.6% decolorization, demonstrating its high catalytic stability. Powder XRD patterns of Mo-Cu-Fe-O before and after reaction are shown in Fig. 9. The crystal structure of the used catalyst is unchanged compared with the fresh catalyst, providing further evidence that the Mo-Cu-Fe-O catalyst is recyclable and retains high catalytic activity after several cycles thanks to its structural stability. The toxicity of the effluent is another important factor, and was

Fig. 9. Powder XRD patterns of Mo-Cu-Fe-O before and after reaction.

Table 1

96h-EC₅₀ values of wastewater containing Cationic Red GTL dye during the degradation reaction.

Reaction time (min)	0	10	20	30	40	50	60
96h-EC ₅₀ (mg/L)	1.07	1.45	1.98	2.13	2.43	2.75	3.01

measured by its toxicity to algae. The 96h-EC₅₀ values (against algae) of wastewater containing Cationic Red GTL were calculated as a function of time during the degradation reaction, and the values are given in Table 1. The 96h-EC₅₀ value of the effluent rose with the increase of elapsed time, suggesting that the toxicity of the effluent was reduced as the degradation proceeded.

3.6. Verification of the proposed mechanism using ESR

To determine the main active species responsible for the degradation of Cationic Red GTL, a comparative ESR study of DMPO-•OH adducts under air aeration and N₂ aeration was performed under the scavenger-loaded condition. It has been reported that Mo reacts with O₂ to produce •OH at the surface of the Mo-Zn-Al-O catalyst, which reduces the amount of oxidizing species in the system [26]. As seen from Fig. 10, four characteristic peaks of DMPO-•OH were observed under air aeration. In contrast, no such signal was detected under N₂ aeration, indicating that air is essential to the generation of •OH on the surface of the catalyst. The Mo-Cu-Fe-O catalyst is similar to the Mo-Zn-Al-O catalyst. A free radical chain auto oxidation process was performed to generate •OH radical, then the •OH radical induce the decomposition of dye. The results of O₂-TPD show that in the initial (activation) stage, O₂ was adsorbed on the surface of the Mo-Cu-Fe-O catalyst, and then reacted with the catalyst in the aqueous environment to form a Mo^{5+/4+} intermediate. The statement about Mo⁶⁺ redox transformations is confirmed by the H₂-TPR results, which show two H₂-TPR peaks, corresponding to the reduction of Mo and Cu. These reductions facilitated the dissolution of Mo, leading to its enhanced reducibility in the CWAO process under ambient conditions. During the exchange of electrons among the reac-

tants, a free-radical-chain autoxidation process was initiated to generate •OH radicals, which induced the decomposition of the dye in the wastewater.

4. Conclusions

A Mo-Cu-Fe-O catalyst was prepared by co-precipitation and impregnation. The degradation of Cationic Red GTL, Crystal Violet, and Acid Red over the Mo-Cu-Fe-O catalyst at room temperature and atmospheric pressure was investigated. The Mo-Cu-Fe-O catalyst showed excellent activity at basic pH in the degradation of Cationic Red GTL. Its negative zeta potential is beneficial for the adsorption of cationic dyes in wastewater, and the results of XRD showed that the small crystalline size of the material is responsible for its excellent catalytic activity. In addition, the results of H₂-TPR and CV demonstrated that the reducibility of the Mo-Cu-Fe-O catalyst is important in the CWAO process. Moreover, the active O₂ adsorption sites of the catalyst also play a central role in its catalytic activity. The formation of •OH radicals is the key process in the decomposition of dye compounds in wastewater, and the toxicity of the effluent is decreased after degradation. Finally, the stability test indicated that the Mo-Cu-Fe-O catalyst retained high catalytic activity after seven runs.

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Fig. 10. ESR spectra of DMPO-•OH adducts with air aeration and with N₂ aeration for an aqueous dispersion of the Mo-Cu-Fe-O catalyst.

Graphical Abstract

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Novel-structured Mo-Cu-Fe-O composite for catalytic air oxidation of dye-containing wastewater under ambient temperature and pressure

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A novel-structured Mo-Cu-Fe-O composite showed superior catalytic activity for the degradation of cationic dyes in wastewater through the generation of hydroxyl radicals.

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常温常压湿式催化氧化染料废水的Mo-Cu-Fe-O新型复合催化材料

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摘要: 染料广泛应用于纺织厂、皮革厂以及染发等各个领域。染料废水具有成分复杂、浓度高、色度大和生物难降解等特性, 因此传统的处理方法难以将其完全降解。高级氧化技术已成为国内外广泛应用的染料废水处理技术之一, 特别是湿式催化氧化(CWAO)技术。然而, CWAO工艺中反应往往需要高温(通常为200–280 °C)和高压(通常为2–9 MPa), 制约了其广泛应用。因此, 人们致力于研发具有高催化活性的催化剂, 通过改变反应历程和降低反应的活化能, 使反应在常温常压条件下进行。

本课题组曾采用钼酸盐浸渍于Zn/Al LDHs溶液中成功制备了Mo/Zn-Al LDHs催化剂, 该催化剂能在常温常压下湿式催化氧化降解阳离子红GTL有机废水。Mo/Zn-Al LDHs催化剂中Mo作为主催化成分, Zn-Al LDHs作为载体。Cu-Fe LDHs本身作为一种催化剂, 与Mo相结合能有效提高催化剂的活性及稳定性, 因此本文采用浸渍法制备了Mo-Cu-Fe-O新型复合催化材料, 采用X射线衍射、氢气程序升温还原、循环伏安法和氧气程序升温脱附等表征手段研究了Mo-Cu-Fe-O材料的结构及氧化还原特性。以阳离子红GTL、结晶紫和酸性红为染料废水代表, 研究了常温常压下Mo-Cu-Fe-O催化降解染料废水的催化活性。结果表明, 在中性条件下Mo-Cu-Fe-O对阳离子型染料废水具有良好的催化活性。循环使用七次后该样品对阳离子红GTL和酸性红的脱色率分别达到91.5%和92.8%, 然而对酸性红阴离子型染料废水基本无催化活性。在常温常压CWAO过程中产生的羟基自由基能有效降解阳离子GTL废水, 其废水毒性随着反应的进行逐渐减小。

关键词: Mo-Cu-Fe-O催化剂; 常温常压; 染料废水; 羟基自由基; 氧化降解

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