

The practical application and electron transfer mechanism of SR-Fenton activation by FeOCI

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Abstract

An efficient FeOCl for persulfate (PS) and peroxymonosulfate (PMS) catalysis was synthesized by one-step method, followed by the exploration of structure and morphology using a range of techniques, such as XPS, FT-IR and SEM. Catalytic mechanism of FeOCl for PS and PMS was investigated to demonstrate its excellent catalytic performance. The results indicated that FeOCl had loose structure, large specific surface area and exposed active sites. Its strong Fe-O and Fe-Cl bonds could promote electron transfer, thereby accelerating the reduction of Fe^{3+} and improving the catalytic rate and utilization rate of oxidants. Since FeOCl had unique and superior structure, it could be used to catalyze 2 persulfates PS and PMS to degrade tetracycline hydrochloride (TTCH) and had good degradation efficiency and degradation stability. When prepared at 250 °C, FeOCl had the best catalytic performance. After 60 min, the degradation rate of TTCH under FeOCI/PS system was 78%, and under FeOCI/PMS system was 81%. After ten cycles, the degradation rate of TTCH still reached 80%. And this catalytic system had wide adaptability to pH. This work highlighted the catalytic versatility of FeOCl in persulfate and proved its application in the treatment of toxic organic wastewater through actual wastewater treatment experiment, which provided a scientific basis for enhancing catalytic performance of FeOCl.



Graphic abstract

Keywords FeOCl \cdot SO₄⁻⁻ \cdot Aops \cdot Tetracycline hydrochloride \cdot Fenton

Introduction

One of the important goals of water purification and wastewater treatment is to remove toxic organic pollutants effectively [1–3]. The advanced oxidation processes (AOPs) show unique advantages in the degradation of toxic organic pollutants [4–6]. Because SO_4^{--} has a higher redox potential than 'OH and can mineralize more toxic organic pollutants, the sulfate-based Fenton-like technology (SR-Fenton) has received more attention [7–9]. In addition, compared with 'OH, SO_4^{--} has a longer half-life and can maintain higher activity in neutral or alkaline water [10, 11]. Therefore, it has greater advantages to use SO_4^{--} to degrade the toxic organic pollutants with benzene ring structure in wastewater [12, 13]. SO_4^{--} can be produced by activating PS and PMS through ultrasound and UV irradiations, carbon-based materials, semiconductors, transition metals and heat [14–16].

Due to the high efficiency and low cost, transition metals (such as Co, Mn and Fe) are considered as effective activators of SR-Fenton [17-21]. However, the carcinogenic effect of cobalt on the human body has limited the application of cobalt ions and cobalt-containing materials. Iron and iron-containing materials are widely used to activate persulfates due to their environmental friendliness and low cost. However, due to the secondary pollution caused by the introduction of a large number of ferrous ions and the technical bottleneck of pH limitation, SR-Fenton is difficult to apply on a large scale [22]. To overcome the shortcomings of SR-Fenton, a series of heterogeneous catalysts have been developed, such as Fe₃O₄ [23], Fe₂O₃ [24], and FeOOH [25]. However, heterogeneous catalysts usually have complex synthetic process, higher cost, and single selectivity to oxidants. The shortcomings of high metal reduction rate and insufficient oxidant decomposition make it difficult to further improve the catalytic efficiency. Repeated changes in metal valence also lead to reduced catalyst stability, and it is difficult to pursue catalytic efficiency and stability at the same time. Comprehensive factors limit the application of catalysts in actual wastewater [26-29]. Therefore, it is of great significance and necessity to explore a new type of iron-based activator, which can quickly recover high-value metals, maintain the stability of structure and performance, and can also be applied in practice.

Recently, the traditional functional material iron oxychloride (FeOCl) has been used to treat organic pollutants in water [30]. It can catalyze the H_2O_2 to form OH at a very high rate, which is 2–4 orders of magnitude higher than other iron-based heterogeneous catalysts [31]. FeOCl has proven to be an excellent heterogeneous catalyst owing to the reducible electronic properties and unique structural configuration of iron atoms [32]. Zhang found that the change of surface state plays an important role in improving the catalytic performance of FeOCl [33]. Recently, FeOCl has been proven to be effective in activating PMS to degrade 6 organic compounds [34]. This further indicates that FeOCl can be used to treat toxic organic pollutants. However, the internal mechanism of the excellent catalytic performance and stability of

FeOCl, as well as its future as a new generation of industrial catalysts, requires further evaluation.

In this work, FeOCl is synthesized by a simple one-step method to catalyze PS and PMS to degrade tetracycline hydrochloride (TTCH). The result shows that the prepared FeOCl has high catalytic efficiency for both PS and PMS, indicating that the catalyst has catalytic universality for oxidants. A series of characterization techniques such as XPS, FT–IR and SEM are used to explore the structure and morphology of FeOCl. Finally, the wastewater treatment equipment is designed to degrade the actual wastewater, and the possible catalytic mechanism is discussed in combination with theory and practice. This work proves the universality of FeOCl for catalyzing persulfates and highlights its practical application in the treatment of toxic organic wastewater.

Materials and methods

Materials

All reagents supplied by Sinopharm Chemical Reagent Co., Ltd. and Shanghai Aladdin Biochemical Technology Co., Ltd. are of analytical grade and used as received without further purification.

Experimental procedure

Fifty milligram of catalyst was evenly mixed in an aqueous solution (100 mL) of TTCH (20 mg/L) and PS/PMS (100 mg/L). In a given time interval, a certain amount of solution was collected, and the concentration of TTCH was measured by detecting the UV–Vis absorption spectrum of the solution.

Preparation of catalyst

FeOCl was prepared through heating anhydrous FeCl_3 powder in a partial pyrolysis method. Specifically, take 2 g of anhydrous FeCl_3 in the agate mortar and grind it thoroughly at a glove box in argon, and smear it evenly on the bottom of the porcelain crucible. Then the sealed sample was raised to corresponding temperature (200 °C, 250 °C, 300 °C and 350 °C) at a rate of 5 °C /min and held for 80 min in a muffle furnace. After natural cooled to room temperature, the sample was ground to powder and subsequently centrifuged with a large amount of anhydrous acetone and then placed in a vacuum drying box at 60 °C for 8 h.

Characterization of catalyst

The catalyst was characterized by multi-techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM), infrared (IR), Raman spectroscopy, X-ray photoelectron spectroscopy (XPS) and Brunauer–Emmet–Teller (BET).

Results and discussion

Characterization of catalyst

The XRD was used to examine the structure of catalyst as shown in Fig. 1a, in which when the temperature was 200 °C and 250 °C, peaks appeared at 11.5°, 26.5°,35°, 38.2° and 46°, respectively, which could be indexed to the (010), (110), (021), (111) and (031) planes of FeOCI (JCPDS No. 24-1005). The degree of crystallinity of the FeOCI at 200 °C was significantly lower than the FeOCI at 250 °C. This result might be due to more crystal defects, larger specific surface area and more exposed active sites at 250 °C. However, when the temperature rose to 300 °C and 350 °C, the peaks of Fe₂O₃ began to appear, which was in line with the standard card of Fe₂O₃ (JCPDS No.33-0664) [31]. Therefore, the catalyst prepared at the temperature of 300 °C and 350 °C was Fe₂O₃/FeOCI. Furthermore, BET analysis was to determine the exposure of the active sites on the surface of FeOCI (Fig. 1b). FeOCI at 250 °C showed stronger absorption at higher N₂ pressure than FeOCI at 200 °C, indicating a larger pore size and more exposured active sites. The surface area of FeOCI at 250 °C was determined to be 19.0187 m²/g. This structure might lead to higher catalytic performance [35].

The microstructure of the samples was characterized by SEM, as shown in Fig. 2. When the temperature was 200 °C and 250 °C, the catalyst samples were layered, and the layers appeared loose. The structure of FeOCl at 250 °C was more loose than FeOCl at 200 °C and might have a larger specific surface area and more active sites. The result was consistent with the XRD and BET analysis. When the temperature rose to 300 °C and 350 °C, there were agglomerations between the sample layers, and the distance between the blocks was relatively close and the combination was tight [36].

To further study the internal structure of FeOCl, FT–IR measurement was carried out as shown in Fig. 3. Two distinct peaks that appeared at about 1619.94 and 3387.27 cm^{-1} corresponded to stretching vibration and bending vibration of OH



Fig.1 a XRD patterns and b N_2 adsorption–desorption isotherms of prepared catalysts at 200 °C, 250 °C, 300 °C and 350 °C



Fig. 2 SEM patterns of prepared catalysts calcined at various temperatures by partial pyrolysis method: a 200 °C; b 250 °C; c 300 °C and d 350 °C



Fig. 3 FT-IR spectra of catalysts: a full spectrum and b High-resolution spectra

group and the water adsorbed on the surface of FeOCl, respectively. This result was beneficial to the adsorption of surface hydroxyl groups and promoted to the generation of free radicals. The peaks at about 492 and 682 cm^{-1} were ascribed to the

stretching vibration of the Fe–O bonds. The peak at about 427 cm⁻¹ was ascribed to the stretching vibration of the Fe–Cl bonds. The peaks of FeOCl at 250 °C at 427 cm⁻¹, 492 cm⁻¹ and 682 cm⁻¹ were shifted to short wavelengths, indicating that the Fe–O and Fe–Cl bonds were stronger due to the dipole moment change of the molecule. Stronger Fe–O and Fe–Cl bonds facilitated electron transfer, promoted Fe³⁺ reduction, and improved catalytic performance and stability [30].

In addition, the Raman spectrum of the FeOCl (Fig. 4) exhibited a band at 216 cm^{-1} that could be attributed to Fe–Cl stretching mode, while the bands appearing at 285 and 400 cm⁻¹ could be attributed to Fe–O stretching modes. The shift of the Raman peaks showed a change in the polarizability of the molecule, and the interaction between Fe–O and Fe–Cl bonds was stronger, which promoted electron transfer and was beneficial to its catalytic performance [37].

According to XPS, it was found that most Fe in FeOCl had a valence state of Fe³⁺ (Fig. 5b). The peaks of the Fe 2p spectrum at 711.98 and 725.73 eV corresponded to 2p 3/2 and 2p 1/2 in Fe³⁺. The peak of the Fe 2p 3/2 at 714.23 eV meant the presence of a trace amount of Fe²⁺. Furthermore, the observed O 1 s peak (530.21 eV) (Fig. 5c) and Cl 2p peak (198.87 eV) (Fig. 5d) indicated the presence of the Fe–O and Fe–Cl bonds [38].

Catalytic activity of FeOCI

In order to explore the optimal crystallization temperature, the performance of the catalyst prepared at different temperatures was compared under PS and PMS (Fig. 6a and b). The results showed that the catalyst prepared at 250 °C had the best performance compared with others. After 60 min, the degradation rate with PS reached 78%, and the degradation rate with PMS reached 81%. The corresponding degradation kinetics are shown in Fig. 6c and d. It could be seen that the degradation rate of the catalyst prepared at 250 °C was higher than those at other temperatures. This further verified that the catalyst prepared at 250 °C had



Fig. 4 Raman spectra of catalysts: a full spectrum and b High-resolution spectra



Fig. 5 XPS spectra of the FeOCl. a Survey; b Fe 2p; c O 1 s; d Cl 2p

optimal catalytic performance because of its larger specific surface area, more exposure sites, and stronger Fe–O bonds.

TTCH degradation results under various conditions with FeOCl prepared at 250 °C are presented in Fig. 7a and b. The results showed that FeOCl alone had almost no adsorption effect on TTCH, whose adsorption rate was only 6%. The degradation rate of TTCH by PS alone was only 16% and by PMS alone was 42.5%. After adding FeOCl, the degradation rate of TTCH under the FeOCl/PS system increased to 75% after 30 min of reaction and increased to 81% under the FeOCl/PMS system, showing the excellent catalytic performance of FeOCl. The corresponding kinetic diagrams are depicted in Fig. 7c, which showed a good linear relationship, confirming the first-order kinetic model in the catalytic reaction effect. The degradation constants (k) of FeOCl/PS system and FeOCl/PMS system are 0.012 and 0.011 min⁻¹, respectively. It could be seen that the catalytic efficiency of FeOCl/PMS system was higher than that of FeOCl/PS system. This result might be due to the large specific surface area of FeOCl and the exposed active sites; moreover, the Fe–O bonds and Fe–Cl bonds promoted electron transfer, leading to the excellent catalytic performance of FeOCl for persulfate [39,



Fig. 6 Comparison of different catalysts **a** PS and **b** PMS on TTCH degradation and corresponding degradation kinetics under (c) PS system and **d** PMS system. Conditions: [Catalyst]=500 mg/L, [PMS]=[PS]=100 mg/L, [TTCH]=20 mg/L, pH=4

40]. From the catalytic experiment of FeOCl on PS and PMS, it could be seen that the activation efficiency of FeOCl on PMS was higher than that of PS. This might be due to the different molecular structure of PMS and PS. The anionic structural formulas of PS and PMS are as follows:



Nown from the corresponding literature that PS had a symmetrical structure, with an O–O bond distance of 1.497 Å and a bond energy of 140 kJ/mol, which had high stability. The structure of PMS was asymmetric, with an O–O bond distance of 1.497 Å and a bond energy 140–213.3 kJ/mol, and its stability was lower than that of PS. Therefore, the O–O bond of PMS was more easily broken, and more easily activated by the catalyst [41].

In order to further prove the excellent catalytic performance of FeOCl, the degradation products were identified by LC–MS shown in Fig. 8a. The main mass peaks at 305.1, 261.1, 130.3, 103.1, 101.1 and 79.1 m/z were attributed to the



Fig.7 Comparison of **a** FeOCl/PS and **b** FeOCl/PMS on TTCH degradation, and **c** the degradation kinetics of 2 systems. Conditions: [FeOCl]=500 mg/L, [PMS]=[PS]=100 mg/L, [TTCH]=20 mg/L, pH=4

intermediates. Based on the possible molecular structure and m/z of the intermediates, we concluded that the TTCH molecule was attacked by the main active substances and degraded into low molecular weight organic compounds. Finally, the intermediate products were mineralized into CO_2 and H_2O , as evidenced by TOC analysis (Fig. 8b). It could be seen from the TOC data that after 60 min of reaction, the mineralization rate of TTCH was 55%. The possible mineralization and degradation pathways of TTCH were proposed (Fig. 8c) [42].

The degradation results of TTCH in FeOCI/PS and FeOCI/PMS systems under a wide range of pH condition are shown in Fig. 9a and b. With the pH increasing from 3.0 to 11.0, there was no significant change in the removal rate of TTCH, but as the pH decreased or increased, the degradation efficiency of TTCH also slightly decreased. It could be seen from the zeta potential characterization (Fig. 9c) that the isoelectric point of FeOCl was pH = 6.1. It could be inferred that when pH > 6.1, the catalyst surface was negatively charged with HSO₅⁻ and S₂O₈²⁻ to form electrostatic repulsion, and the activation efficiency of the catalyst on PS and PMS was reduced. When the pH was less than 6.1,



Fig.8 a The HPLC–MS spectra of tetracycline degradation process and b TOC spectra of tetracycline degradation process and c possible degradation pathways of TTCH

the positive charge on the surface of the catalyst formed electrostatic adsorption with HSO_5^- and $S_2O_8^{2-}$, and the activation efficiency of the catalyst on PS and PMS would increase. These results indicated that FeOCl had an excellent pH adaptation range and was an excellent industrial catalyst [43].

Stability of FeOCl

In order to test the stable performance, FeOCl was subjected to 10 cycle experiments. The result is shown in Fig. 10a and b, which indicated that under the same conditions, FeOCl still had high degradation efficiency (80%) after ten catalytic experiments. The leaching amount in the first cycle under the FeOCl/PS system was 1.65 ppm and under the FeOCl/PMS system was 1.86 ppm. In the subsequent cycle experiments, the leaching amount gradually decreased. After 10 cycles, the leaching amount under the 2 systems was 0.38 and 0.52 ppm, respectively. The homogeneous degradation experiment of the same Fe ion leaching amount under the 2 systems of FeOC1/PMS was also implemented, and the results are shown in Fig. 7a and b. It could be seen that for the degradation of TTCH, PS and PMS and Fe ions leached into the solution had a certain contribution rate, but the main role was the surface effect of the catalyst. The FT–IR and XPS spectrums of FeOCl (Fig. 11a and b) after cyclic reaction further indicated that its structure had no noticeable change, proving the good stability [44].



Fig. 9 Degradation of TTCH under different initial pH values in the **a** FeOCI/PS and **b** FeOCI/PMS and **c** point of zero charge (pHpzc) of FeOCI. Conditions: [FeOCI]=500 mg/L, [PMS]=[PS]=100 mg/L, [TTCH]=20 mg/L, pH=4



Fig. 10 Cycling curve for catalytic degradation of TTCH in the **a** FeOCI/PS and **b** FeOCI/PMS. Conditions: [FeOCI]=500 mg/L, [PMS]=[PS]=100 mg/L, [TTCH]=20 mg/L, pH=4



Fig. 11 a FT-IR and b XPS patterns of FeOCl fresh and FeOCl recycled under PS or PMS

Catalytic degradation of other organic pollutants of FeOCI

In order to prove the versatility of FeOCl for organic pollutant treatment, three other pollutants including rhodamine B (RhB), bisphenol A (BPA) and carbamazepine (CBZ) were oxidized, as shown in Fig. 12. The result showed that FeOCl had excellent degradation ability for all 3 pollutants. Therefore, in general, it can be said that FeOCl was a good activation catalyst for PS and PMS and had excellent degradation ability for difficult-to-degrade organic compounds.

Mechanism discussion

In order to investigate the mechanism of FeOCl catalysis, the main free radicals in the catalytic process were initially determined by free radical inhibition experiments (Fig. 13). After adding the ethanol (EtOH), tert-butanol (TBA) and P-benzoquinone (BQ), the TTCH removal rates were reduced to 43, 50 and 77%, respectively, demonstrating that SO_4^{--} and 'OH were dominant in the catalytic degradation reaction under FeOCl/PS system. And also, under the FeOCl/PMS

Fig. 12 Degradation of various robust organic compounds. Conditions: [FeOCI] = 500 mg/L, [PMS] = [PS] = 100 mg/L, [Rh B] = [BPA] = [CBZ] = 20 mg/L, pH=4





Fig. 13 FeOCl catalytic activity for a PS and b PMS with different scavengers

system, with the addition of EtOH, TBA and BQ, the removal rates of TTCH decreased to 19, 41, and 53%, respectively, demonstrating that OH was dominant in the catalytic degradation reaction, followed by SO_4^{--} [40].

To further confirm this result, the free radicals were analyzed using the EPR technology. As shown in Fig. 14, the peaks of 'OH and SO_4 ⁻⁻ radicals could be observed in both the FeOCI/PS and FeOCI/PMS systems. This result was consistent with the inhibition experiment result, further verifying the main role of 'OH and SO_4 ⁻⁻ [39].

The spectrums of XPS before and after the reaction were used to study the reaction mechanism further (Fig. 15). The change in Fe 2p peak area indicated that the relative content of Fe^{2+}/Fe^{3+} increased from 0.20 to 0.31 under FeOCl/PS system and from 0.2 to 0.25 under FeOCl/PMS system. The results revealed that more Fe^{2+} was regenerated due to the interaction of Fe–O and Fe–Cl bonds [31, 45]. Meanwhile, due to the weak interaction between Fe and Cl, the Cl atoms on the FeOCl surface could be lost in the water. The loss of Cl atoms caused the



Fig. 14 DMPO spin-trapping EPR spectra for a FeOCI/PS and b FeOCI/PMS



Fig. 15 XPS (Fe 2p) patterns of FeOCl a fresh and FeOCl recycled under b PS or c PMS

unsaturated Fe atom coordination to become highly reactive sites, which was beneficial to trap HSO_5^- and $\text{S}_2\text{O}_8^{2-}$ and react with TTCH [46].

According to the above discussion and results, a possible mechanism of FeOCl catalyzing PS and PMS is illustrated in Fig. 16. FeOCl had loose structure, larger



Fig. 16 Plausible mechanism for FeOCl/PS and FeOCl/PMS

specific surface area and exposed active sites. Moreover, the presence of unsaturated iron atoms (such as Fe²⁺) on the surface of FeOCl could effectively catalyze PS and PMS. Due to the unique structure of FeOCl (such as Fe²⁺, Fe–O and Fe–Cl bonds), Fe³⁺ in FeOCl can be rapidly reduced to Fe²⁺ by charge transfer, thereby increasing the catalytic rate and oxidant utilization rate [30, 34, 47]. In addition, under FeOCl/PMS system, PMS can react with SO₄ ⁻⁻ and OH to form SO₅⁻⁻ species with lower reactivity (Eqs. 1 and 2), and SO₅⁻⁻ species can further self-react to form PS (Eq. 3) [15, 48].

$$HSO_5^- + SO_4^- \to HSO_5^- + SO_5^{--}$$
(1)

$$HSO_5^- + OH \rightarrow H_2O + SO_5^-$$
 (2)

$$2SO_5^{--} \to S_2O_8^{2-} + O_2 \tag{3}$$

Practical application

In order to put the catalyst into practical application, a water purification device for the laboratory was designed to simulate industrial wastewater treatment. Place FeOCl in the filter, and make the TTCH and PMS solutions flow through the catalyst membrane (Fig. 17a). The experiment simulated four real water bodies, including deionized water, tap water, underground water and surface water. The TTCH solution was effectively degraded after passing through the FeOCl catalyst filter. For deionized water, the TTCH was degraded by 95%, and then tap water, groundwater, and surface water were added in order. The degradation rates of the solution could reach 82, 72 and 67% (Fig. 17b). Simulation experiment proved that the catalyst had good stability even in the continuous purification treatment of different real water bodies.



Fig. 17 a Configuration of TTCH flow-through degradation experiment and b degradation rate of TTCH in different water bodies. Reaction conditions: [TTCH] = 10 mg/L, [PMS] = 200 mg/L, flow speed = 8 ml/min

Conclusion

This work synthesized an efficient catalyst FeOCl for PS and PMS catalysis in a simple one-step process. The results showed that FeOCl had a loose structure, larger specific surface area and exposed active sites. Its strong Fe–O and Fe–Cl bonds could promote electron transfer, thereby accelerating the reduction of Fe³⁺ and increasing the catalytic rate and oxidant utilization rate. By using the unique and favorable structure of FeOCl to catalyze PS and PMS, the excellent degradation efficiency and stability for TTCH could be achieved, indicating that FeOCl had catalytic universality and high efficiency for persulfate. In addition, FeOCl aimed to verify the feasibility in practical applications. The results showed that FeOCl can effectively remove pollutants from various real water bodies. This work highlighted the application of FeOCl in the treatment of toxic organic wastewater and provided a scientific basis for improving the catalytic performance of FeOCl.

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References

- 1. J.-R.L.C.-C. Wang, X.-L. Lv, Y.-Q. Zhang, G. Guo, Energy Environ. Sci. 9, 2831 (2014)
- 2. H. Shao, X. Zhao, Y. Wang, et al., Appl. Catal. B: Environ. 218, 810 (2017)
- 3. F.Z.Q. Han, C. Hu, L. Lv, Z. Zhang, N. Chen, L. Qu, Nano Research 5, 1718 (2015)
- 4. C. Sun, S.T. Yang, Z. Gao et al., Mater. Chem. Phys. 223, 751 (2019)
- 5. B.T.S. Wang, W. Yang et al., Alloy. Compd. 784, 1099 (2019)
- 6. J.M.X. Zhang, C. Fan et al., J. Alloy. Compd. 785, 343 (2019)
- 7. B.W.J. Wu, L. Blaney et al., Chem. Eng. J. 361, 99 (2019)
- 8. L.T.J. Yu, Y. Pang et al., Chem. Eng. J. 364, 146 (2019)
- 9. X. Li, X. Liu, C. Lin et al., Chem. Eng. J. 367, 208 (2019)
- 10. X. Pang, Y. Guo, Y. Zhang et al., Chem. Eng. J. 304, 897 (2016)
- 11. X. Xu, J. Qin, Y. Wei et al., Chem. Eng. J. 365, 259 (2019)
- 12. H. Li, J. Wan, Y. Ma et al., J. Hazard. Mater. 318, 154 (2016)
- 13. L. Zhu, J. Ji, J. Liu, S. Mine, M. Matsuoka, J. Zhang, M. Xing, Angew. Chem. Int. Ed. Engl. 33, 13968 (2020)
- 14. B. Kakavandi, N. Bahari, R. Rezaei-Kalantary, E. Dehghani-Fard, Ultrason. Sonochem. 55, 75 (2019)
- 15. R. Khaghani, B. Kakavandi, K. Ghadirinejad, E. Dehghani-Fard, A. Asadi, Microporous Mesoporous Mater. 284, 111 (2019)
- M. Noorisepehr, K. Ghadirinejad, B. Kakavandi, A. Ramazanpour-Esfahani, A. Asadi, Chemosphere 232, 140 (2019)
- 17. H. Wang, W. Guo, R. Yin et al., Chem. Eng. J. 362, 561 (2019)
- 18. J.P. Zhu, Y.L. Lin, T.Y. Zhang et al., Chem. Eng. J. 367, 86 (2019)
- 19. Z.D.W. Shang, M. Li, X. Song, M. Zhang, C. Jiang, S. Feiyun, Chem. Eng. J. 361, 1333 (2019)
- 20. D. Ozer, O. Icten, N. Altuntas-Oztas, B. Zumreoglu-Karan, Res. Chem. Intermed. 1, 909 (2019)
- 21. Y. Peng, L. Zhou, L. Wang, J. Lei, Y. Liu, S. Daniele, J. Zhang, Res. Chem. Intermed. 12, 5907 (2019)
- 22. J.L.H. Lim, S. Jin, J. Kim, J. Yoon, T. Hyeon, Chem. Commun. 4, 463 (2006)
- 23. J.W.L. Xu, Appl. Catal. B 123, 117 (2012)
- 24. X.H.S.X.F. Chen, X. Qiu, J. Hazard. Mater. 322, 152 (2017)

- 25. X. Li, Y. Huang, C. Li et al., Chem. Eng. J. 260, 28 (2015)
- 26. Q.Y.C. Wang, Z. Li, K.-Y.A. Lin, S. Tong, Sep. Purif. Technol. 213, 447 (2019)
- 27. K.H.H. Dong, W. Qiao, Y. Cheng, L. Zhang, B. Wang, L. Li, Y. Wang, Q. Ning, G. Zeng, Chem. Eng. J. **359**, 1046 (2019)
- 28. H. Hu, H. Zhang, Y. Chen et al., Chem. Eng. J. 368, 273 (2019)
- G.F.Y. Song, C. Zhu, F. Zhu, S. Wu, N. Chen, T. Wu, Y. Wang, J. Gao, D. Zhou, Chem. Eng. J. 355, 65 (2019)
- C.C.M. Sun, F. Geng, X. Lu, J. Qu, J. Crittenden, M. Elimelech, J.-H. Kim, Environ. Sci. Technol. Lett. 3, 186 (2018)
- 31. X.-M.X.X.-J. Yang, J. Xu, Y.-F. Han, J. Am. Chem. Soc 43, 16058 (2013)
- 32. X.-M. X. X.-J. Yang, X.-C. Xu, J. Xu, H.-L. Wang, R. Semiat, Y.-F. Han, Catal. Today 85 (2016)
- 33. X.L.J.J. Zhang, Y.G. Xia, F.F. Liu, Y.P. Pang, X.F. Zhao, D.R. Chen, Chem. Eur. J. 27, 9321 (2016)
- 34. Y.L.Y. Chen, L. Zhang, P. Xie, Z. Wang, A. Zhou, Z. Fang, J. Ma, J. Hazard. Mater. 353, 18 (2018)
- 35. H. X. S. Zuo, W. Liao, X. Yuan, L. Sun, Q. Li, J. Zan, D. Li, D. Xia, Colloids Surf. Physicochem. Eng. Asp. 307 (2018)
- H.X.S. Zuo, W. Liao, L. Sun, D. Han, J. Zan, B. Zhang, D. Li, D. Xia, Appl. Organomet. Chem. 9, 448 (2018)
- 37. G.L.J. Zhang, S. Liu, New J. Chem. 9, 6896 (2018)
- 38. H. Zhong, L. Duan, P. Ye, X. Li, A. Xu, Q.A. Peng, Res. Chem. Intermed. 3, 907 (2018)
- 39. H.X.M. Chen, X. Zhang, D. Li, D. Xia, J. Mater. Res. 21, 3549 (2018)
- 40. S. Zuo, H. Xu, W. Liao et al., Chem. Phys. Lett. 699, 241 (2018)
- 41. J. Wang, S. Wang, Chem. Eng. J. 334, 1502 (2018)
- 42. L.Z.F. Deng, X. Luo, S. Luo, D.D. Dionysiou, Chem. Eng. J. 333, 423 (2018)
- 43. G. Wu, W. Qin, L. Sun et al., Chem. Eng. J. 360, 115 (2019)
- 44. H.X.M. Chen, Q. Wang, D. Li, D. Xia, Chem. Phys. Lett. 706, 415 (2018)
- 45. M.W.D. Wang, Z. Li, ACS Catal. 11, 6852 (2015)
- 46. J. Zhang, X.L. Jiao, Y.G. Xia, F.F. Liu, Y.P. Pang, X.F. Zhao, D.R. Chen, Chemistry 27, 9321 (2016)
- 47. M. Xing, W. Xu, C. Dong, Y. Bai, J. Zeng, Y. Zhou, J. Zhang, Y. Yin, Chem 6, 1359 (2018)
- M. Kermani, F. Mohammadi, B. Kakavandi, A. Esrafili, Z. Rostamifasih, J. Phys. Chem. Solids 117, 49 (2018)

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