

Magnetically Recoverable Fe₂O₃/ZSM-5 Composite for Fenton-Like Oxidation of Organic Dyes in Water

Yang Song

Shandong Jianzhu University

Zhaochen Dong

Shandong Jianzhu University

Shuying Li

shuyingli@mail.sdu.edu.cn

Shandong Jianzhu University

Wenmei Zhao

Shandong Jianzhu University

Yanzhen Wang

Shandong Jianzhu University

Xianglong Zhao

Shandong Jianzhu University

Yang Zhao

Shandong Coal Field Geological Survey and Research Institute

Xiuqin Sun

Shandong Coal Field Geological Survey and Research Institute

Mulan Zhu

Xiamen University of Technology

Wei Fan

Northeast Normal University

Feiyong Chen

Shandong Jianzhu University

Research Article

Keywords: Heterogeneous Fenton-like reaction, Zeolite, Wastewater treatment, Magnetic separation

Posted Date: October 7th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10770185/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Magnetically Recoverable Fe₂O₃/ZSM-5 Composite for Fenton-Like Oxidation of Organic Dyes in Water

Yang Song¹, Zhaochen Dong¹, Shuying Li^{1,*}, Wenmei Zhao¹, Yanzhen Wang¹, Xianglong Zhao¹,
Yang Zhao², Xiuqin Sun^{2,*}, Mulan Zhu³, Wei Fan⁴, Feiyong Chen¹

¹ Resources and Environment Innovation Institute, Shandong Jianzhu University, Jinan 250101,
Shandong Province, China.

² Shandong Coal Field Geological Survey and Research Institute, Jinan 250100, Shandong
Province, China.

³ School of Environmental Science and Engineering, Xiamen University of Technology, Xiamen
361024, China

⁴ School of Environment, Northeast Normal University, 2555 Jingyue Street, Changchun 130117,
China

*Corresponding Authors: Email: shuyingli@mail.sdu.edu.cn (Shuying Li);
18653177227@126.com (Xiuqin Sun)

Abstract

A magnetic Fe₂O₃-modified ZSM-5 catalyst was synthesized via excessive impregnation for heterogeneous Fenton-like degradation of Rhodamine B (RhB) in dye wastewater. The catalyst possesses well-dispersed iron oxide species and a stable structure, achieving 95.0 % degradation efficiency under optimized conditions. It exhibits excellent magnetic recyclability, avoiding the generation of iron sludge, which is a major drawback of traditional Fenton systems.. Mechanistic studies confirm that hydroxyl radicals generated through Fe²⁺/Fe³⁺ cycling are responsible for RhB mineralization to CO₂ and H₂O. The catalyst maintains stable performance over multiple cycles. This work offers a sustainable, environmentally friendly solution for dye wastewater treatment with efficient catalyst recovery and reduced secondary pollution.

Keywords: Heterogeneous Fenton-like reaction; Zeolite; Wastewater treatment; Magnetic separation.

1. Introduction

With the rapid development of industry, the volume of dye wastewater discharged has steadily increased(Solayman et al. 2023). Rhodamine B (RhB), as a typical cationic dye, poses a severe threat to the ecological environment and human health due to its high toxicity, difficulty in degradation, and potential carcinogenicity(Liu et al. 2021). Traditional methods for treating dye wastewater, such as physical adsorption(El-Kammah et al. 2022), chemical oxidation(Agarwala and Mulky 2023), and biological degradation(Li et al. 2019), suffer from issues like

low treatment efficiency, high cost, and the potential for secondary pollution. Therefore, it is of utmost urgency to develop efficient, environmental friendly, and cost-effective technologies for dye wastewater treatment.

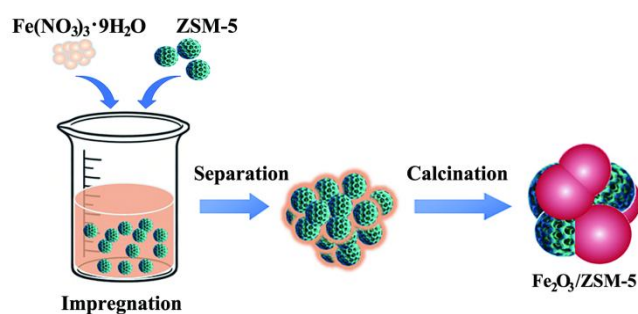
Advanced oxidation processes (AOPs) have emerged as promising alternatives for the degradation of organic pollutants in wastewater(Li et al. 2024, Mahbub and Duke 2023, Zango et al. 2025). Among them, the Fenton process(Ji et al. 2025, Lin et al. 2022), which involves the reaction between hydrogen peroxide (H_2O_2) and Fe ions to generate highly reactive hydroxyl radicals ($\cdot\text{OH}$), has attracted extensive attention due to its strong oxidizing ability and relatively simple operation(Du et al. 2022, Kirchon et al. 2020). For example, in a groundwater project for chlorinated hydrocarbon pollution remediation, the Fenton technology can cut pollutant levels by over 60% in a short time(Zhou et al. 2024b). However, the conventional homogeneous Fenton system suffers from critical limitations, including strict acidic pH requirements, excessive iron sludge production, and low H_2O_2 utilization efficiency(Yang et al. 2025, Zeng et al. 2025). To overcome these limitations, heterogeneous Fenton-like catalysts including have been developed, including Iron based materials(Sun et al. 2023), transition metal materials(Wang et al. 2022), metal oxides(Soufi et al. 2024), carbon materials(Fang et al. 2024), and composite materials(Ma et al. 2025). Heterogeneous Fenton-like reactions involve a series of chemical processes where heterogeneous catalysts are utilized to activate oxidizing agents containing peroxide groups like H_2O_2 , peroxysulfate oxidants, etc. The efficiency of the heterogeneous Fenton-like reactions depends on substance transfer, active site activation, and regeneration(Chen et al. 2024, Xie et al. 2022). Therefore,

increasing the specific surface area of the Fe₂O₃/ZSM-5 through morphological modification can greatly improve material transfer to enhance catalytic efficiency, such as porous material modification.

Zeolites, particularly ZSM-5 zeolite, have been widely used as catalyst supports due to their unique properties(Bensafi et al. 2023, Shannon et al. 2025, Sun et al. 2021). ZSM-5 zeolite, with its ordered microporous channels, high surface area, and robust thermal/chemical stability, is an excellent support for loading active metals to prepare heterogeneous catalysts(Cheng et al. 2023, Gu et al. 2021). The microporous structure of ZSM-5 can disperses loaded metal species and confines catalytic reactions, which may enhance the catalytic activity and selectivity(Tomina et al. 2022). Several studies have demonstrated the effectiveness of iron-loaded zeolite catalysts in the degradation of organic pollutants. For example, Jiang and coworkers(Rao et al. 2021) developed a hierarchically porous Fe-ZSM-5 bead material with three-dimensional continuous pore channels, which demonstrated exceptional performance in Fenton-like reactions, achieving near-complete degradation of methylene blue and phenol within 1.5 hours. Tian et al.(Tian et al. 2024) demonstrated that Fe-ZSM-5 zeolites effectively degrade 1,4-dioxane via heterogeneous Fenton oxidation. Zhou et al.(Zhou et al. 2024a) developed a Fe-ZSM-5/H₂O₂ Fenton system that selectively degraded 93.7% of formaldehyde with 98.2% selectivity over glucose, operating stably across a wide pH range. Therefore, heterogeneous Fenton-like systems employing iron-based catalysts have emerged as a promising alternative, offering advantages such as broader pH adaptability, reduced metal leaching, and recyclability of catalysts. However, despite many efforts

to improve the degradation efficiency of iron-based catalysts, there are still limitations in the exploration of porous iron-based nanocatalyst materials for magnetic recycling. Therefore, further in-depth research on the environmentally friendly iron-based catalysts with magnetic recoverability remains an important direction.

In this study, a solid magnetic Fe oxides modified ZSM-5 ($\text{Fe}_2\text{O}_3/\text{ZSM-5}$) was successfully synthesized via excessive impregnation (**Scheme 1**). Immobilizing the synthetic Fe_2O_3 onto the ZSM-5 carrier enhances the catalyst's magnetic properties, which in turn facilitates its recovery and minimizes secondary pollution. RhB aqueous solution was chosen to simulate dye-contaminated wastewater for assessing the degradation performance of the $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ catalyst. Through meticulous optimization of the experimental variables, this magnetic catalyst achieved an optimal degradation efficiency of up to 95.0 % and exhibited excellent reusability. In addition, this method can also achieve efficient reuse by the magnetic recycling, providing a feasible approach for the resource utilization and recycling of iron containing wastewater.



Scheme 1. Schematic diagram of the synthesis of $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ catalyst

2. Experimental section

2.1 Materials

Iron nitrate nonahydrate, ZSM-5 molecular sieve was purchased from Shanghai Macklin Biochemical Co.,Ltd. Ultrapure water is used in the experiment.

2.2 Preparation of Fe₂O₃/ZSM-5

Iron nitrate nonahydrate and ZSM-5 molecular sieve were chosen as catalytic agents at this experiment. Typically, 4.04 g Iron nitrate nonahydrate was dissolved in 100 ml purified water, then dispersed using an ultrasonic bath. 2.8 g ZSM-5 was rapidly injected into 100 ml purified water. After 5 min, the obtained impregnated solution was transferred to magnetic stirrer for 12h. Later, the impregnation were collected after filtration and dried under 60 °C. Finally, the impregnation were calcined for 2h to obtain the Fe₂O₃/ZSM-5 materials. A series of Fe₂O₃/ZSM-5 materials were prepared under different conditions of 500 °C, 600 °C, 700 °C, 800 °C, and 900 °C, with only varying roasting temperatures.

2.3 Materials characterization

The experiment employs five model instruments to assess catalytic performance: a Scanning Electron Microscopy (SEM) machine manufactured by the German Zeiss company, an X - ray Diffraction (XRD) machine of the Japan Riken SmartLab type, a Brunauer - Emmett - Teller specific surface area (BET) measurement device using the American Micromeritics 3Flex instrument, and an X-ray Photoelectron Spectroscopy (XPS) device, specifically the Thermo ESCALAB 250Xi from Thermo Fisher Scientific. SEM and Energy Dispersive X-ray Spectroscopy (EDS) techniques are utilized to determine the crystal morphology and chemical element composition. The XRD technique, utilizing Cu - K α 1 radiation at 40 mA and 40 kV,

is employed to identify the iron oxide phase and estimate the crystallinity. The BET technique is used to determine the material's specific surface area, average pore diameter, average pore volume, pore size, and other relevant parameters. The XPS technique is applied to analyze the $\text{Fe}_2\text{O}_3/\text{ZSM-5}$'s surface chemical compositions and valence states.

2.4 Catalytic properties

The experiment was conducted under standard conditions of room temperature. Initially, taking 100 mL 20mg/L Rhodamine B (RhB) dye wastewater solution as the target. Subsequently, the $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ was uniformly dispersed in 25.0 ml of the RhB dye wastewater solution with a concentration of 0.02 mg/ml. Immediately, a certain amount of a 30% H_2O_2 solution was rapidly introduced into the mixture. At 20 minute intervals, 2.0 ml samples were taken from the solution. The sample was separated using a magnet and collect the supernatant for subsequent the analysis of the RhB's absorbance. According to the above conditions, change the catalyst dosage to 60 mg, 70 mg, 80 mg, 90 mg, and 100 mg respectively to explore the catalytic effect. Next, adjust the dosage of hydrogen peroxide to 0.5 mL, 1.0 mL, 1.5 mL, 2.0 mL, and 2.5 mL respectively to investigate the catalytic effect and optimize the amount of hydrogen peroxide. Change the reaction temperature by 20 °C, 30 °C, 40 °C, 50 °C, and 60 °C respectively to investigate the effect of reaction temperature.

2.5 Mechanism investigation

As a common free radical scavenger, tert-butanol effectively neutralizes free radicals through redox mechanisms. In this part, a series of tert-butanol solutions with different concentrations (0.2 mol/L, 0.4 mol/L, 0.6 mol/L, and 0.8 mol/L) were

prepared. These pre-configured solutions were used to prepare 100 mL solutions containing 20 mg/L RhB solution, respectively. Take the tert butanol concentration as control and explore the degradation effect of RhB.

3. Results and discussion

The microstructure of the $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ was analysed by typical SEM. As shown in **Fig. 1a/b**, the uniform spherical structure of the $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ nanoparticles can be observed, and the size of the catalyst rapidly reached approximately 70 nm. Low-magnification Transmission electron microscopy (TEM) images of $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ crystals presented the irregular spherical shape (**Fig. 1c**) and the dispersion of Fe_2O_3 nanoparticles on the ZSM-5 carrier was observed. The lattice spacing of 0.279 nm and 0.152 nm corresponded to high index (221) and (521) crystal planes of Fe_2O_3 , respectively (**Fig. 1d/e**, Fig. S1), which might be the main catalytic active center that dominates its efficient reaction performance. Additionally, the selected area electron diffraction (SAED) pattern confirms the polycrystalline structure of $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ (**Fig. 1f** and Fig. S2). Elemental mapping analysis of the spatial distribution of Fe element has been performed in **Fig. 1g**. The distribution of these metal elements appears to be relatively uniform across the surface with a good dispersion, allowing the preparation of ZSM-5 loaded with highly dispersed Fe_2O_3 nanoparticles. EDS of $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ composites also provides the evidence that Fe_2O_3 catalyst has been generated on the ZSM-5 carriers (Table S1).

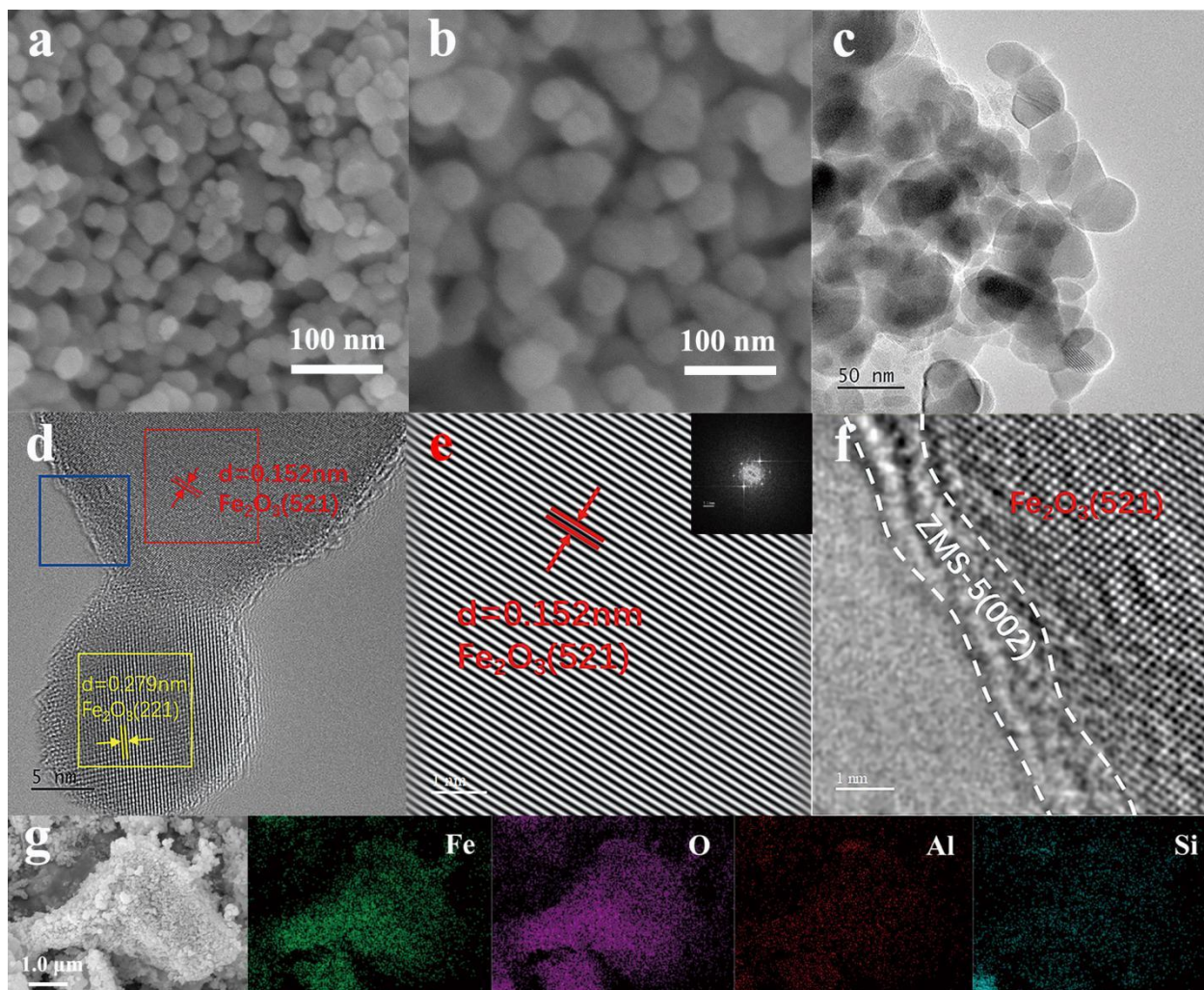


Fig. 1 The SEM image of uniform a $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ composites and b their enlarged image; c TEM and (d-f) HRTEM images and (g) the elemental mapping of $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ composites

The X-ray diffraction (XRD) patterns of the ZSM-5, Fe_2O_3 , and $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ catalyst with the highly crystalline structures were presented in **Fig. 2a**. The diffraction peaks at 33.1° , 35.6° , and 54.0° were assigned to (1 0 4), (1 1 0), and (1 1 6) planes, respectively, which correspond to the typical peaks of Fe_2O_3 (JCPDS no. 89-0597)(Wu et al. 2023). The diffraction peaks at 8.8° was assigned to (2 0 0) plane off ZSM-5 crystal(Cui et al. 2024, Xu et al. 2021). Notable, the XRD diffraction peaks indicate that Fe_2O_3 successfully adheres to ZSM-5 carriers without altering the crystal structure of the support. This is because the mesoporous structure of

ZSM-5 also provides a uniform attachment area for Fe_2O_3 nanoparticles, preventing aggregation and ensuring the dispersion of active sites. Meanwhile, the complete crystal structure ensures the mechanical and thermal stability of the catalyst, making it less prone to deactivation during repeated use or high-temperature reactions. **Fig. 2b** depicts nitrogen adsorption-desorption isotherms of ZSM-5 carrier, revealing a BET specific surface area of $276.5 \text{ m}^2/\text{g}$. The hysteresis loop and high N_2 adsorption at low pressures indicate a rich mesoporous structure with narrow slit like pores, mainly below 20nm with a concentration at 2.7 nm. **Fig. 2c** presents the $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ calcined has a BET specific surface area of $261.3 \text{ m}^2/\text{g}$ and the hysteresis loop suggests narrow slit-like pores formed by aggregated particles. The reduction of BET specific surface area is attributed to the introduction of iron oxides. The $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ loaded with Fe_2O_3 maintains high N_2 adsorption at low pressure, indicating its rich pore structure. This high specific surface area and mesoporous structure provide sufficient adsorption sites and diffusion channels for organic pollutants. The mesoporous structure facilitates the rapid adsorption and enrichment of pollutant molecules, increases local concentration, and accelerates reaction kinetics. The $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ catalyst provided the ample adhesion area for iron oxides and facilitating rapid adsorption, enhancing contact with metal oxides and catalytic efficiency(Mirshafiee et al. 2022). Meanwhile, the narrow slit like pores promote the mass transfer efficiency of diffusion limited reactions, making it easier for pollutants and oxidants to come into contact with active sites. The structure supports efficient degradation of RhB wastewater, with Fe_2O_3 effectively attaching to ZSM-5 for catalytic oxidation. Moreover, the Fe elemental relationship between its binding

energy and intensity of the Fe 2p orbital was analyzed in the Fig. S3. The peak at 725.2 eV corresponds to the Fe 2p 3/2 state, often associated with Fe(III) species in oxides or hydroxides. The peak at 719.2 eV can be attributed to Fe(II) in similar chemical environments. The peaks at 714.2 eV and 711.5 eV may indicate the presence of Fe in a reduced state or in complex compounds, possibly due to interactions with the support or other dopant species in the Fe₂O₃/ZSM-5. Multivalent iron species are the core active sites for catalytic oxidation reactions. When H₂O₂ is activated by the catalyst, the cycling between Fe (II) and Fe (III) can efficiently generate ·OH radicals to accelerate the attack on pollutant RhB molecules. Meanwhile, the acid sites of the ZSM-5 molecular sieve not only stabilize Fe species and promote the cycling of Fe ions in different valence states, but also can polarize RhB to make it more easily oxidized. In addition, strong interactions may form at the interface between Fe₂O₃ and ZSM-5, enhancing electron transfer and improving the activation efficiency of oxidants.

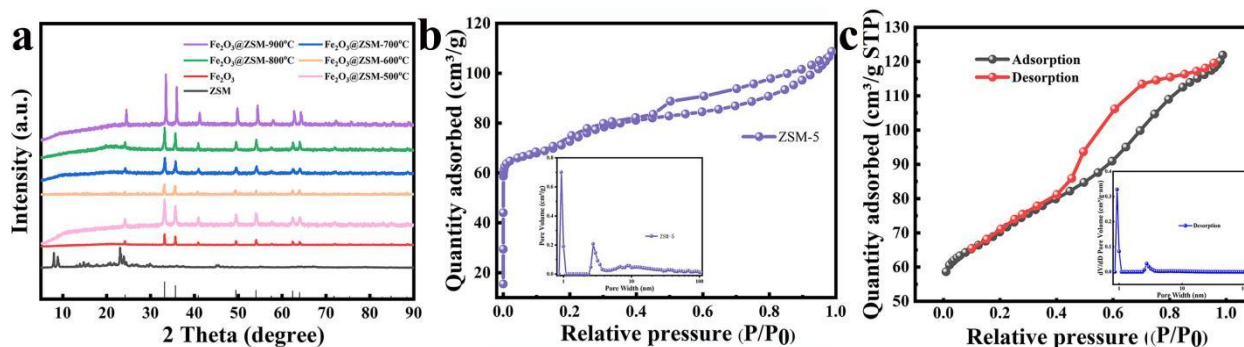


Fig. 2 a XRD patterns of ZSM-5, Fe₂O₃, and Fe₂O₃/ZSM-5 composites. The N₂ adsorption-desorption isotherm of b ZSM-5 and c Fe₂O₃/ZSM-5 composites

The catalytic activity of the obtained catalyst was estimated by employing the

reduction of RhB dye with the H_2O_2 oxidation. In Fig. S4, the standard curve was painted to read the absorption corresponding to the RhB's concentration, and can see that the RhB have fine correlation between the adsorption and the concentration. The adsorption measurements at different concentrations are as follows: 0.19 at 5 mg/L, 0.372 at 10 mg/L, 0.566 at 15 mg/L, and 0.756 at 20 mg/L. The data were fitted to a linear model, yielding the equation $y = -0.0014 + 0.03806 \cdot x$, with a correlation coefficient of 0.9997. In addition, a series of follow-up experiments were conducted to determine the optimal parameters of the $\text{Fe}_2\text{O}_3/\text{ZSM-5}$. In **Fig. 3a/b**, the degradation rate of RhB treated by $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ was significantly higher than that of ZSM-5 alone and the blank control, demonstrating the enhanced catalytic activity conferred by the Fe_2O_3 modification. The difference in degradation efficiency between the single carrier catalyst and the loaded Fe_2O_3 can be attributed to the unique redox properties of iron species (Zeng et al. 2023). The presence of Fe_2O_3 can facilitate the formation of reactive oxygen species, enhancing the degradation effect. Moreover, the roasting temperature critically determines the catalytic performance of $\text{Fe}_2\text{O}_3/\text{ZSM-5}$. **Fig. 3c/d** depict that the calcination temperature significantly affected the catalytic efficiency of $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ for RhB degradation. The efficiency peaked at 82.9% at 800 °C, in stark contrast to the lowest value of 28% observed at 500 °C. This disparity is attributed to the fact that appropriate high temperatures can create more active sites and increase surface area, thereby enhancing pollutant contact and degradation. However, excessively high temperatures may destroy these active sites and impede catalytic interactions (Zhao et al. 2024). Therefore, 800 °C was selected as the optimal temperature.

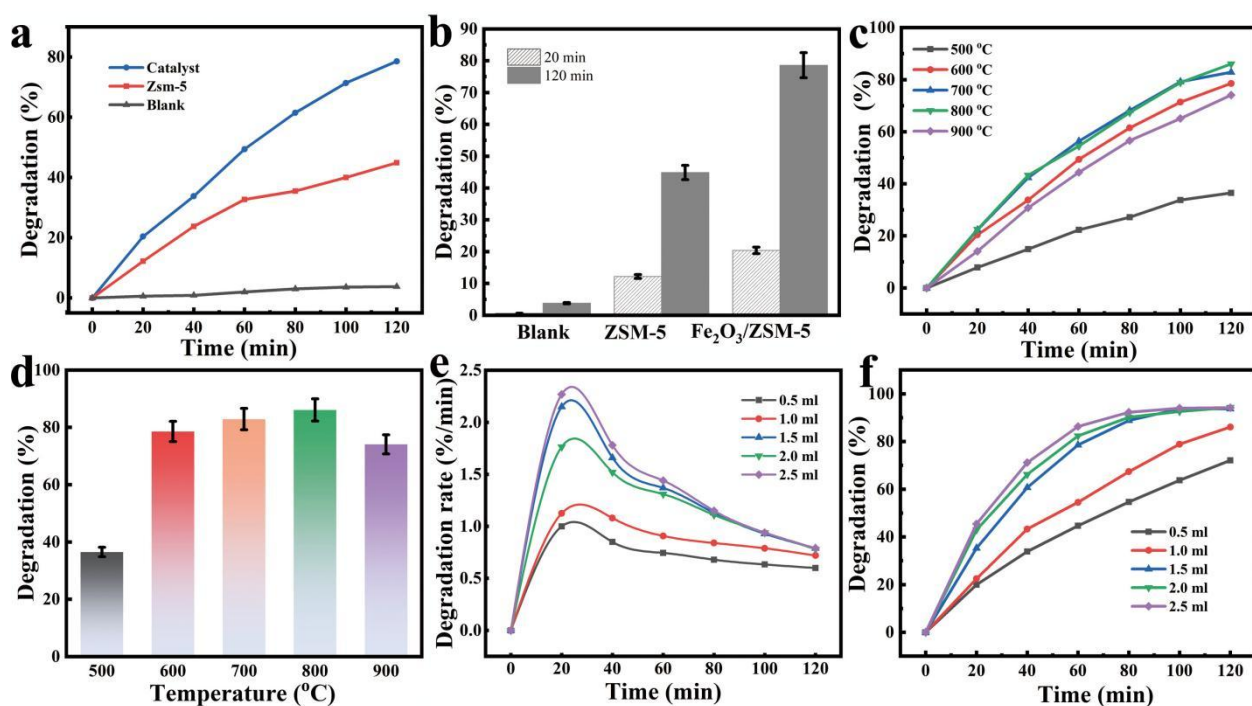


Fig. 3 **a** The degradation of the RhB solution treated by blank, ZSM-5, and Fe₂O₃/ZSM-5, and **b** their corresponding time-dependent comparison of degradation efficiency. **c** The influence of the calcination temperature on the catalytic efficiency of Fe₂O₃/ZSM-5 for RhB degradation and **d** their corresponding time-dependent comparison of degradation efficiency. **e** The degradation rate and **f** the degradation efficiency varies with the H₂O₂ dosage

As a common oxidant in Fenton-like systems, the dosage of H₂O₂ is known to significantly influence the process efficiency. When only H₂O₂ was added, the degradation rate of Rhodamine B only reached 6%, while when only the catalyst was added, it resulted in a slight increase in the color of the wastewater (Fig. S5). Therefore, the main mechanism of simulating dye wastewater with RhB is efficient catalytic oxidation and the catalyst application in combination with oxidants is necessary for dye removal. Furthermore, the effect of oxidant dosage on the oxidation reaction was investigated. **Fig. 3e** presents the degradation velocity as a function of H₂O₂ dosage. The peak degradation rate at 25 min for the 2.5 mL H₂O₂

dosage was 2.8 times higher than that for 0.5 mL. Correspondingly, the degradation ratio exceeded 80% at 120 min for 2.5 mL, representing a 1.3 fold increase over the one with 0.5 mL H₂O₂ (**Fig. 3f**). This enhanced efficiency with increasing H₂O₂ concentration is attributed to the greater ·OH generation(Khan et al. 2023).

The experiment was conducted at different temperatures to evaluate the catalytic performance (**Fig. 4a/b**). The Fe₂O₃/ZSM-5 catalyst exhibited the highest efficiency of 95.0 % at 60 °C, while the lowest efficiency of 92.0 % was observed at 20 °C. This is mainly attributed to the influence of temperature on reaction kinetics. Higher temperatures increase the diffusion rate and kinetic energy of Rh. B molecules, making them easier to contact and utilize the active sites inside the catalyst, thereby exhibiting higher apparent catalytic activity. On the contrary, at lower temperatures, molecular diffusion is limited and the active surface of the catalyst is not fully utilized. However, it is crucial to note that excessively high temperatures might lead to catalyst deactivation or sintering, reducing its long-term stability and effectiveness(Zhang et al. 2024). The effect of catalyst addition on RhB degradation was evaluated. In **Fig. 4c**, it can be seen that as the dose gradually increases from 60mg to 90mg, the degradation efficiency gradually increases. When the amount of catalyst added exceeds 90 mg, the degradation efficiency reaches a peak. However, catalysts at higher doses showed a decreasing trend, possibly due to aggregation reducing the available active sites for degradation reactions (**Fig. 4d**) (Belrhazi et al. 2025). Therefore, the optimal dosage of catalyst at 60 °C is 90mg, which can produce the highest performance.

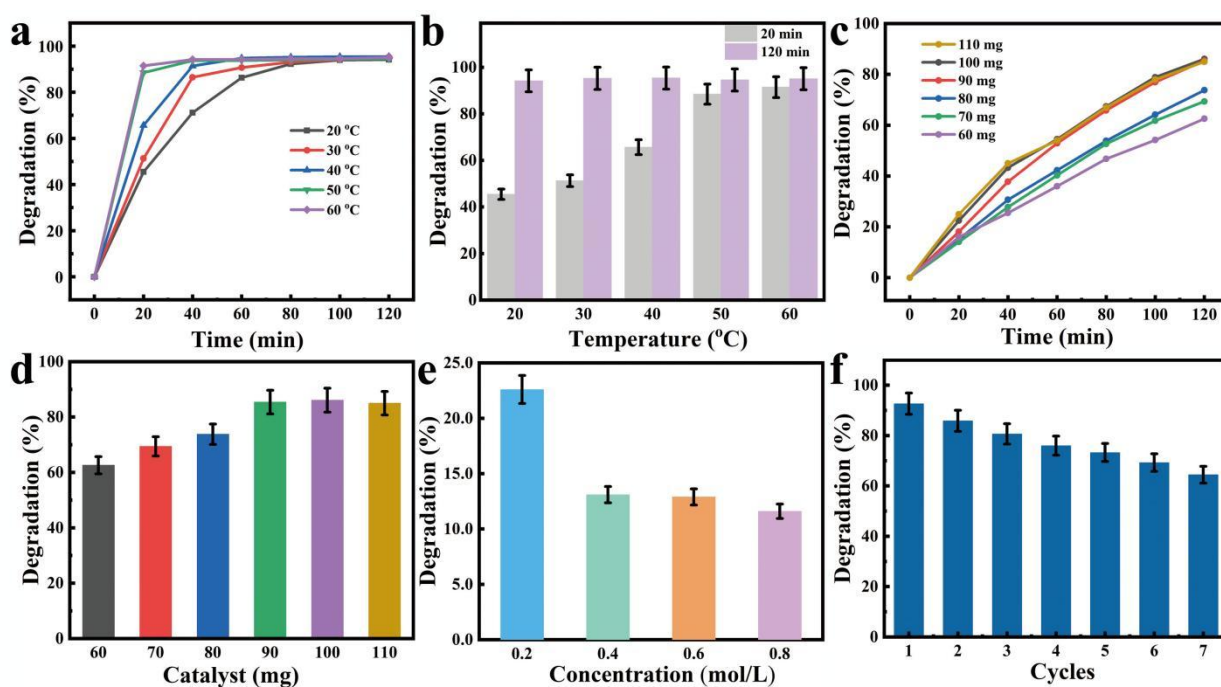


Fig. 4 **a** The influence of the reaction temperature on the catalytic efficiency of Fe₂O₃/ZSM-5 for RhB degradation and **b** their corresponding time-dependent comparison of degradation efficiency. **c** The effect of catalyst dosage on the catalytic efficiency of Fe₂O₃/ZSM-5 for RhB degradation and **d** their corresponding degradation efficiency in 120 min. **e** The influence of the addition of tert-butanol and **f** the cycle stability test on the catalytic efficiency of Fe₂O₃/ZSM-5 for RhB degradation

By tracking free radicals through, the impact of the effective free radicals within Fe₂O₃/ZSM-5 is to be investigated. ·OH and other reactive free radicals were neutralized by the addition of tert-butanol. As illustrated in **Fig. 4e**, when the concentration of tert-butanol was increased from 2 mol/L to 8 mol/L, a gradual decline in the degradation efficiency of RhB catalyzed by the Fe₂O₃/ZSM-5 composite was observed. The underlying cause of this trend was the degradation of RhB predominantly depended on the reaction between the Fe₂O₃/ZSM-5 composite

and hydrogen peroxide. This reaction led to the generation of a substantial quantity of $\cdot\text{OH}$, which subsequently targeted and broke down large molecular pollutants (Mu et al. 2022). However, it was observed that the introduction of tert-butanol suppressed the production of $\cdot\text{OH}$, consequently resulting in a reduction in the degradation rate. This outcome provided further corroboration that $\cdot\text{OH}$ play a key role in the catalytic degradation of RhB by the $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ catalyst. Additionally, the degradation extent of RhB over multiple usage cycles was assessed to ascertain the influence of repeated catalytic cycles on its degradation performance. **Fig. 4f** depicts the experiment to trial the catalytic degradation efficiency influencing of cycle times. A progressive decline in degradation rate was observed with magnetic recycling. The sharpest reduction, nearly 6% relative to the initial efficiency, occurred between the first and second cycles. After seven cycles, the overall catalytic activity decreased by approximately one-quarter of its original value. The catalyst's stable performance further demonstrates its robust recyclability. These results collectively demonstrate the advantageous interaction between the $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ and the oxidation H_2O_2 . Furthermore, The specific mechanism of the reaction can be elucidated through the following equations, and the schematic heterogeneous Fenton catalytic mechanism of $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ is discussed in **Fig. 5** based on relevant literature. Initially, Fe^{2+} on the surface of Fe_2O_3 triggers a chain reaction to produce $\cdot\text{OH}$ (Eq. 1). Then, Fe^{3+} reacts with H_2O_2 to generate Fe^{2+} , $\cdot\text{OOH}$, and H^+ , which is the key to the cycle. This reaction reduces the generated Fe^{3+} back to Fe^{2+} (Eq.2), completing the catalytic cycle. In addition, through the physical/chemical adsorption of ZSM-5, RhB and H_2O_2 were enriched near the surface of Fe_2O_3 , which

can greatly increase the probability of reaction collision. The acidic sites and defects on the surface of ZSM-5 might also act as electron transfer bridges to promote the reduction of Fe^{3+} to Fe^{2+} . Meanwhile, $\cdot\text{OOH}$ can dissociate into weakly oxidizing superoxide radicals ($\text{O}_2\cdot^-$) (Eq.3), while $\text{O}_2\cdot^-$ can act as an additional reducing agent to assist in the reduction of Fe^{3+} to Fe^{2+} , accelerating the entire catalytic cycle (Eq.4). $\cdot\text{OH}$ indiscriminately attacks the conjugated chromophore and aromatic ring structure of RhB, ultimately transforming into water and carbon dioxide owing to its potent oxidation capabilities (Eq.5).

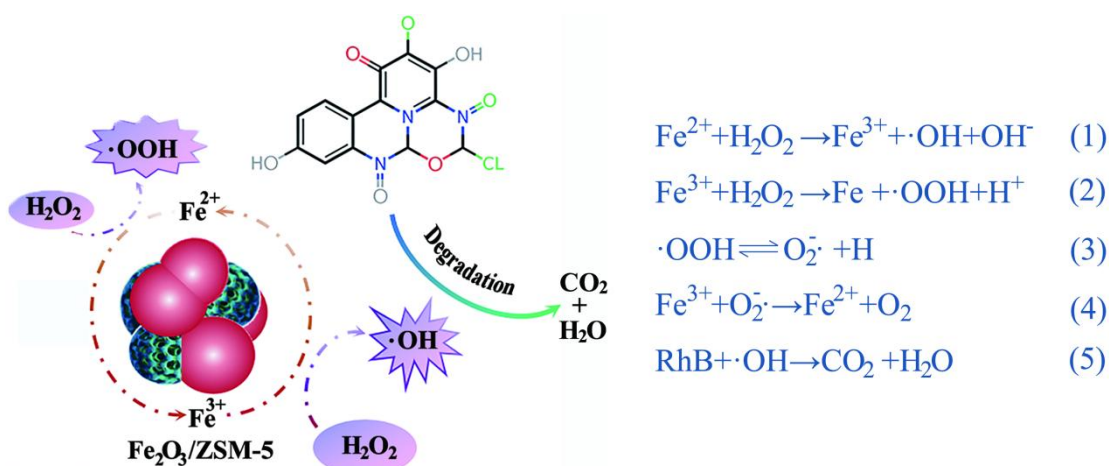


Fig. 5. Schematic heterogeneous Fenton catalytic mechanism diagram of $\text{Fe}_2\text{O}_3/\text{ZSM-5}$

4. Conclusion

In this study, a solid $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ catalyst prepared via excessive impregnation was employed to remove RhB through a heterogeneous Fenton-like reaction. According to the characterization results, the obtained $\text{Fe}_2\text{O}_3/\text{ZSM-5}$ prepared in this experiment had a regular morphology, a favorable structure, and high catalytic degradation efficiency. Taking RhB simulated dye wastewater as example, the optimized reaction conditions were calcination temperature of 800 °C, catalyst

dosage of 90 mg, H₂O₂ dosage of 2.5 mL, and reaction temperature of 60 °C. Further analysis through comparative experiments and radical quenching experiments revealed that the obtained catalyst exhibited remarkable catalytic performance. Mechanism analysis proves that the degradation process primarily relied on the large quantity of ·OH generated by the reaction between the Fe₂O₃/ZSM-5 and H₂O₂. Additionally, the Fe₂O₃/ZSM-5 consistently showed excellent stability catalytic activity during the catalytic degradation process. This obtained magnetic recyclable catalyst can effectively avoid the iron sludge produced in traditional Fenton reactions, rendering it more environmentally friendly. Moreover, this method also facilitates the resource recovery and recycling of iron-containing wastewater by enabling the efficient reuse and recovery of iron ions. Future studies can explore more magnetic recyclable heterogeneous Fenton-like catalysts applied in the purification of wastewater to improve the efficiency.

Statements and Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This work was financially supported by the Key Scientific Research Special Project of the Shandong Provincial Bureau of Coal Geology (MTDZKY-2026).

372

373 **Author information**

374 **Authors and Affiliations**

375 **Resources and Environment Innovation Institute, Shandong Jianzhu University, Jinan**

376 **250101, Shandong Province, China.**

377 Yang Song, Zhaochen Dong, Shuying Li, Wenmei Zhao, Yanzhen Wang, Xianglong Zhao,

378 Feiyong Chen

379 **Shandong Coal Field Geological Survey and Research Institute, Jinan 250100, Shandong**

380 **Province, China.**

381 Yang Zhao, Xiuqin Sun

382 **School of Environmental Science and Engineering, Xiamen University of Technology,**

383 **Xiamen 361024, China**

384 Mulan Zhu

385 **School of Environment, Northeast Normal University, 2555 Jingyue Street, Changchun**

386 **130117, China**

387 Wei Fan

388 **Contributions**

389 **Yang Song:** Supervision, Funding acquisition, Project administration, Writing-

390 review & editing.

391 **Zhaochen Dong:** Validation.

392 **Shuying Li:** Writing-review, Visualization.

393 **Wenmei Zhao:** Investigation, Data curation, Writing-original draft.

394 **Yanzhen Wang:** Investigation.

395 **Xianglong Zhao:** Formal analysis.

396 **Yang Zhao:** Formal analysis.

397 **Xiuqin Sun:** Writing-review.

398 **Mulan Zhu:** Validation.

399 **Wei Fan:** Formal analysis.

400 **Feiyong Chen:** Project administration.

401

402 **Corresponding Authors:** Correspondence to Shuying Li and Xiuqin Sun

403

404 **Ethics declarations**

405 **Ethics Approval and Consent to Participate**

406 Not applicable.

407 **Consent for Publication**

408 All authors in this paper are agree to publish this paper in this journal.

409 **Competing interests**

410 The authors declare that they have no known competing financial interests or
411 personal relationships that could have appeared to influence the work reported in
412 this paper.

413

414 **Data Availability Statement**

415 The datasets generated and/or analyzed during the current study are not publicly
416 available due to the large size of the dataset but are available from the corresponding
417 author on reasonable request.

References

- Agarwala, R. and Mulky, L. (2023) Adsorption of Dyes from Wastewater: A Comprehensive Review. *Chembioeng Reviews* 10(3), 326-335. <https://doi.org/10.1002/cben.202200011>
- Belrhazi, I., Sair, S., Ousaleh, H.A., Faik, A. and Zahouily, M. (2025) Zeolite-based catalysis for plastic waste recycling: Sustainable solutions from laboratory testing to industrial applications. *Renewable & Sustainable Energy Reviews* 222, 27. <https://doi.org/10.1016/j.rser.2025.115945>
- Bensafi, B., Chouat, N. and Djafri, F. (2023) The universal zeolite ZSM-5: Structure and synthesis strategies. A review. *Coordination Chemistry Reviews* 496, 25. <https://doi.org/10.1016/j.ccr.2023.215397>
- Chen, Y.W., Zhu, K., Qin, W.L., Jiang, Z.W., Hu, Z.F., Sillanpa, M. and Yan, K. (2024) Enhanced electron transfer using NiCo₂O₄@C hollow nanocages with an electron-shuttle effect for efficient tetracycline degradation. *Chemical Engineering Journal* 488, 11. <https://doi.org/10.1016/j.cej.2024.150786>
- Cheng, Q.P., Li, G.N., Yao, X.L., Zheng, L.R., Wang, J.H., Emwas, A.H., Castaño, P., Ruiz-Martínez, J. and Han, Y. (2023) Maximizing Active Fe Species in ZSM-5 Zeolite Using Organic-Template-Free Synthesis for Efficient Selective Methane Oxidation. *Journal of the American Chemical Society* 145(10), 5888-5898. <https://doi.org/10.1021/jacs.2c13351>
- Cui, X.X., Lyu, H., Chai, Y.M., Liu, B., Zhao, D.F. and Liu, C.G. (2024) Selective aromatization of 1-hexene to BTX over core-shell structured Silicalite-1@ZSM-5 catalyst. *Separation and Purification Technology* 349, 12. <https://doi.org/10.1016/j.seppur.2024.127881>

440 Du, C.Y., Zhang, Y., Zhang, Z., Zhou, L., Yu, G.L., Wen, X.F., Chi, T.Y., Wang, G.L., Su, Y.H.,
 441 Deng, F.F., Lv, Y.C. and Zhu, H. (2022) Fe-based metal organic frameworks (Fe-MOFs) for
 442 organic pollutants removal via photo-Fenton: A review. *Chemical Engineering Journal* 431, 18.
 443 <https://doi.org/10.1016/j.cej.2021.133932>
 444 El-Kammah, M., Elkhatib, E., Gouveia, S., Cameselle, C. and Aboukila, E. (2022) Cost-effective
 445 ecofriendly nanoparticles for rapid and efficient indigo carmine dye removal from wastewater:
 446 Adsorption equilibrium, kinetics and mechanism. *Environmental Technology & Innovation* 28, 10.
 447 <https://doi.org/10.1016/j.eti.2022.102595>
 448 Fang, J.F., Liu, L., Yang, H. and Du, H.Y. (2024) Applications of Fenton/Fenton-like photocatalytic
 449 degradation in g-C₃N₄ based composite materials. *Journal of Environmental Chemical*
 450 *Engineering* 12(6), 25. <https://doi.org/10.1016/j.jece.2024.114153>
 451 Gu, Y., Chen, P.P., Wang, X.H., Lyu, Y.C., Liu, W.R., Liu, X.M. and Yan, Z.F. (2021) Active Sites
 452 and Induction Period of Fe/ZSM-5 Catalyst in Methane Dehydroaromatization. *Acs Catalysis*
 453 11(12), 6771-6786. <https://doi.org/10.1021/acscatal.1c01467>
 454 Ji, J.H., Gao, Y.Z. and Zhang, X.S. (2025) A comparative study on the water treatment effects of
 455 different advanced oxidation technologies in a water treatment system based on double-sided
 456 photovoltaic-thermoelectric generators. *Renewable Energy* 242, 15.
 457 <https://doi.org/10.1016/j.renene.2025.122412>
 458 Khan, Z.U., Gul, N.S., Sabahat, S., Sun, J.Y., Tahir, K., Shah, N.S., Muhammad, N., Rahim, A.,
 459 Imran, M., Iqbal, J., Khan, T.M., Khasim, S., Farooq, U. and Wu, J.B. (2023) Removal of organic
 460 pollutants through hydroxyl radical-based advanced oxidation processes. *Ecotoxicology and*
 461 *Environmental Safety* 267, 15. <https://doi.org/10.1016/j.ecoenv.2023.115564>

462 Kirchon, A., Zhang, P., Li, J.L., Joseph, E.A., Chen, W.M. and Zhou, H.C. (2020) Effect of
 463 Isomorphic Metal Substitution on the Fenton and Photo-Fenton Degradation of Methylene Blue
 464 Using Fe-Based Metal-Organic Frameworks. *Acs Applied Materials & Interfaces* 12(8), 9292-
 465 9299. <https://doi.org/10.1021/acsami.9b21408>
 466 Li, F., Liu, K.W., Bao, Y.P., Li, Y.X., Zhao, Z.Y., Wang, P.F. and Zhan, S.H. (2024) Molecular level
 467 removal of antibiotic resistant bacteria and genes: A review of interfacial chemical in advanced
 468 oxidation processes. *Water Research* 254, 18. <https://doi.org/10.1016/j.watres.2024.121373>
 469 Li, W., Mu, B.N. and Yang, Y.Q. (2019) Feasibility of industrial-scale treatment of dye wastewater
 470 via bio-adsorption technology. *Bioresource Technology* 277, 157-170.
 471 <https://doi.org/10.1016/j.biortech.2019.01.002>
 472 Lin, R.Y., Li, Y., Yong, T.Z., Cao, W.X., Wu, J.S. and Shen, Y.F. (2022) Synergistic effects of
 473 oxidation, coagulation and adsorption in the integrated fenton-based process for wastewater
 474 treatment: A review. *Journal of Environmental Management* 306, 15.
 475 <https://doi.org/10.1016/j.jenvman.2022.114460>
 476 Liu, Y., Zhao, Y. and Wang, J.L. (2021) Fenton/Fenton-like processes with in-situ production of
 477 hydrogen peroxide/hydroxyl radical for degradation of emerging contaminants: Advances and
 478 prospects. *Journal of Hazardous Materials* 404, 20. <https://doi.org/10.1016/j.jhazmat.2020.124191>
 479 Ma, D.S., Lai, C., Yi, H., Huo, X.Q., Li, L., Zhang, M.M., Xu, F.H., Yan, H.C., Hu, S.Y. and Luo,
 480 Y.C. (2025) Confinement strategies for the design of efficient heterogeneous Fenton-like catalysts:
 481 From nano-space to atomic scale. *Coordination Chemistry Reviews* 522, 32.
 482 <https://doi.org/10.1016/j.ccr.2024.216241>

483 Mahbub, P. and Duke, M. (2023) Scalability of advanced oxidation processes (AOPs) in industrial
 484 applications: A review. *Journal of Environmental Management* 345, 12.
 485 <https://doi.org/10.1016/j.jenvman.2023.118861>
 486 Mirshafiee, F., Khoshbin, R. and Karimzadeh, R. (2022) A green approach for template free
 487 synthesis of Beta zeolite incorporated in ZSM-5 zeolite to enhance catalytic activity in MTG
 488 reaction: Effect of seed nature and temperature. *Journal of Cleaner Production* 361, 11.
 489 <https://doi.org/10.1016/j.jclepro.2022.132159>
 490 Mu, S.J., Lu, H.L., Wu, Q.B., Li, L., Zhao, R.J., Long, C. and Cui, C.H. (2022) Hydroxyl radicals
 491 dominate reoxidation of oxide-derived Cu in electrochemical CO₂ reduction. *Nature*
 492 *Communications* 13(1), 8. <https://doi.org/10.1038/s41467-022-31498-8>
 493 Rao, W., You, C.Z., Jiang, Y.Q., Guo, X.T., Li, D.F., Xu, X.Z. and Lin, K.F. (2021) Iron-doped
 494 hierarchically porous Fe-ZSM-5 zeolite with 3D continuous pore architecture for catalytical
 495 degradations. *Materials Chemistry and Physics* 271.
 496 <https://doi.org/10.1016/j.matchemphys.2021.124704>
 497 Shannon, M.D., Cox, P.A., Mayoral, A., Hsieh, M.F. and Turrina, A. (2025) The Real Structure of
 498 Intergrown ZSM-5/ZSM-11 Industrial Zeolite Catalysts. *Small Structures* 6(10), 11.
 499 <https://doi.org/10.1002/sstr.202500184>
 500 Solayman, H.M., Hossen, M.A., Abd Aziz, A., Yahya, N.Y., Leong, K.H., Sim, L.C., Monir, M.U.
 501 and Zoh, K.D. (2023) Performance evaluation of dye wastewater treatment technologies: A review.
 502 *Journal of Environmental Chemical Engineering* 11(3).
 503 <https://doi.org/10.1016/j.jece.2023.109610>
 504 Soufi, A., Hajjaoui, H., Boumya, W., Elmouwahidi, A., Baillon-Garcia, E., Abdennouri, M. and
 505 Barka, N. (2024) Recent trends in magnetic spinel ferrites and their composites as heterogeneous

506 Fenton-like catalysts: A review. Journal of Environmental Management 367, 36.
507 <https://doi.org/10.1016/j.jenvman.2024.121971>

508 Sun, Q.M., Wang, N. and Yu, J.H. (2021) Advances in Catalytic Applications of Zeolite-Supported
509 Metal Catalysts. Advanced Materials 33(51), 37. <https://doi.org/10.1002/adma.202104442>

510 Sun, W., Wang, S., Yu, Z.C. and Cao, X.L. (2023) Characteristics and application of iron-based
511 materials in heterogeneous Fenton oxidation for wastewater treatment: a review. Environmental
512 Science-Water Research & Technology 9(5), 1266-1289. <https://doi.org/10.1039/d2ew00810f>

513 Tian, K., Pan, J., Liu, Y., Wang, P., Zhong, M., Dong, Y.H. and Wang, M. (2024) Fe-ZSM-5 zeolite
514 catalyst for heterogeneous Fenton oxidation of 1,4-dioxane: effect of Si/Al ratios and contributions
515 of reactive oxygen species. Environmental Science and Pollution Research 31(13), 19738-19752.
516 <https://doi.org/10.1007/s11356-024-32287-0>

517 Tomina, E.V., Kurkin, N.A. and Doroshenko, A. (2022) Synthesis of Nanoparticulate Cobalt
518 Ferrite and Its Catalytic Properties for Fenton-Like Processes. Inorganic Materials 58(7), 701-705.
519 <https://doi.org/10.1134/s0020168522070135>

520 Wang, L.Y., Jiang, H.R., Wang, H., Show, P.L., Ivanets, A., Luo, D. and Wang, C.Q. (2022)
521 MXenes as heterogeneous Fenton-like catalysts for removal of organic pollutants: A review.
522 Journal of Environmental Chemical Engineering 10(6), 20.
523 <https://doi.org/10.1016/j.jece.2022.108954>

524 Wu, R.H., Hu, X., Li, Y.H., Li, Y.F., Cai, Y.J., Jiang, P.K. and Yu, B. (2023) Efficient activation of
525 peroxymonosulfate by amorphous MnO₂/α-Fe₂O₃ for the degradation of organic pollutants.
526 Chemical Engineering Journal 473, 13. <https://doi.org/10.1016/j.cej.2023.145011>

527 Xie, D.H., Guo, P.C., Zhong, K.Q. and Sheng, G.P. (2022) Highly dispersed Co/Fe bimetal in
528 carbonaceous cages as heterogeneous Fenton nanocatalysts for enhanced sulfamethoxazole

529 degradation. *Applied Catalysis B-Environment and Energy* 319, 13.
 530 <https://doi.org/10.1016/j.apcatb.2022.121923>

531 Xu, G.H., Zhang, P., Cheng, J.J., Wei, T., Zhu, X.D. and Yang, F. (2021) Preparation of a hollow
 532 HZSM-5 zeolite supported molybdenum catalyst by desilication-recrystallization for enhanced
 533 catalytic properties in propane aromatization. *Journal of Solid State Chemistry* 300, 9.
 534 <https://doi.org/10.1016/j.jssc.2021.122238>

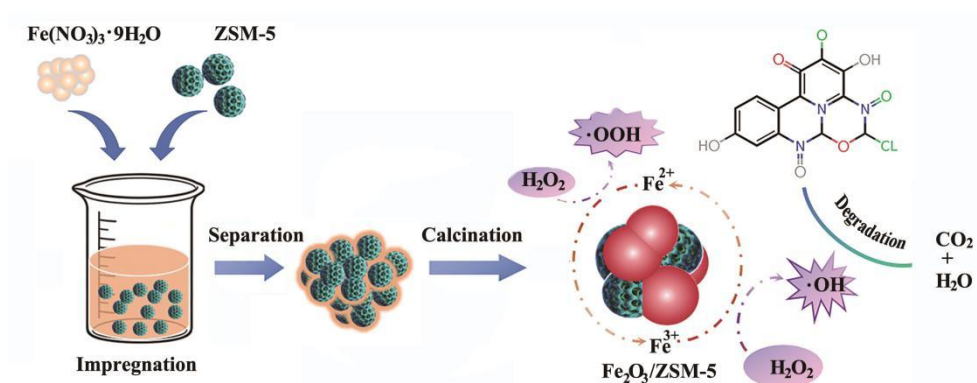
535 Yang, Z.X., Wang, H., Hao, X.B., Zhang, L.Y., Li, Y. and Zhang, G.K. (2025) Regulating facet
 536 exposure and sulfur vacancy in magnetic greigite nanosheet for boosting heterogeneous Fenton-
 537 like reaction towards efficient degradation of metronidazole under visible light irradiation:
 538 Synergistic enhancement effect, DFT calculations and mechanism insight. *Journal of Materials*
 539 *Science & Technology* 216, 27-37. <https://doi.org/10.1016/j.jmst.2024.06.053>

540 Zango, Z.U., Ibnaouf, K.H., Lawal, M.A., Aldaghri, O., Wadi, I.A., Modwi, A., Zango, M.U. and
 541 Adamu, H. (2025) Recent trends in catalytic oxidation of tetracycline: An overview on advanced
 542 oxidation processes for pharmaceutical wastewater remediation. *Journal of Environmental*
 543 *Chemical Engineering* 13(3), 33. <https://doi.org/10.1016/j.jece.2025.116979>

544 Zeng, H.X., Che, Y.B., Yang, B.F., Deng, J., Zhang, C.Y., Wang, J. and Zhang, H.J. (2025)
 545 Differential catalytic mechanism induced by selective adsorption of pollutants in metal clusters
 546 decorated single atom catalyst mediated heterogeneous Fenton-like reaction. *Journal of Hazardous*
 547 *Materials* 491, 10. <https://doi.org/10.1016/j.jhazmat.2025.138029>

548 Zeng, Y.X., Almatrafi, E., Xia, W., Song, B., Xiong, W.P., Cheng, M., Wang, Z.W., Liang, Y.T.,
 549 Zeng, G.M. and Zhou, C.Y. (2023) Nitrogen-doped carbon-based single-atom Fe catalysts:
 550 Synthesis, properties, and applications in advanced oxidation processes. *Coordination Chemistry*
 551 *Reviews* 475. <https://doi.org/10.1016/j.ccr.2022.214874>

552 Zhang, R., Zhang, H.M., Liu, F.Y., Sun, M. and Ma, S. (2024) High temperature oxidation
 553 resistance behavior of Ti₃SiC₂/Cu composites under migration of Ti and Cu atomic. *Ceramics*
 554 *International* 50(23), 49490-49500. <https://doi.org/10.1016/j.ceramint.2024.09.293>
 555 Zhao, Y.Y., Yan, Y.Q., Jiang, Y.H., Cao, Y., Wang, Z.Z., Li, J.P., Yan, C.S., Wang, D.Y., Yuan, L.
 556 and Zhao, G.B. (2024) Release Pattern of Light Aromatic Hydrocarbons during the Biomass
 557 Roasting Process. *Molecules* 29(6), 11. <https://doi.org/10.3390/molecules29061188>
 558 Zhou, P.G., Hou, J.X., Zhang, D.H., Liao, Z.Q., Yang, L.P., Yang, W.J., Ru, X. and Dai, Z.B. (2024a)
 559 Selective Heterogeneous Fenton Degradation of Formaldehyde Using the Fe-ZSM-5 Catalyst.
 560 *Molecules* 29(12), 14. <https://doi.org/10.3390/molecules29122911>
 561 Zhou, Z.Y., Habib, M., Xu, Z.Q., Zeng, G.L., Yang, R.M., Sui, Q. and Lyu, S.G. (2024b)
 562 Remediation performance of different enhanced Fe(II)-based advanced oxidation processes on
 563 groundwater contaminated by multiple mixed chlorinated hydrocarbons: Removal efficiencies,
 564 costs, and optimal systems. *Chemical Engineering Journal* 479, 11.
 565 <https://doi.org/10.1016/j.cej.2023.147670>
 566
 567



Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupportingInformation.docx](#)