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Fe(III)-salen complex supported on dendrimer functionalized magnetite nanoparticles as a highly active and selective catalyst for the green oxidation of sulfides

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Abstract

In this study, we reported the preparation of polyamidoamine-modified magnetite nanoparticles and their use for the immobilization of Fe(III)-salen complex to form a novel magnetic catalyst. The prepared catalyst was characterized by some modern techniques i.e. Fourier transform infrared spectroscopy (FT-IR), thermogravimetric analysis (TGA), N₂ adsorption-desorption analysis, X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), energy-dispersive X-ray spectroscopy (EDX), X-ray photoelectron spectroscopy (XPS), vibrating sample magnetometry (VSM), and inductively couple plasma atomic emission spectroscopy (ICP-AES). The catalyst showed excellent activity and selectivity for the oxidation of sulfides to sulfoxides (conversion 87-100%, selectivity 82-100%) using H_2O_2 (30% w/w) as oxidant in aqueous medium at 50 °C. Furthermore, the catalyst could be recovered in a facile manner from the reaction mixture by using a magnet and reused for five cycles with high catalytic stability.

Keywords: Magnetite nanoparticles; Dendrimer; Immobilization; Fe(III)-salen complex; Oxidation; Sulfide.

Introduction

Selective oxidation of sulfides to their corresponding sulfoxides is a transformation of great interest as the sulfoxide products are important intermediates for the constructing of a variety of chemically and biologically significant molecules such as drugs [1-5]. The most popular and promising route for this transformation is to use transition metal-based catalysts. In this context, manganese, titanium, vanadium, molybdenum, and iron complexes have been applied. Among them, iron-based catalysts have attracted great attentions owing to the high abundance, long-term availability, low cost, and low toxicity of iron [6-8]. Despite the considerable achievements that have been made, these homogeneous catalytic systems are unfortunately associated with many troublesome obstacles in practical applications, in terms of catalyst separation and recycling. To solve these issues, the homogeneous catalysts have been immobilized on various solid supports which improve their recovery and recycling properties [9-13]. However, the catalytic activity and selectivity of most of these supported catalysts decreases upon immobilization because of the low active sites availability [14,15]. Thus, it is highly desirable and necessary to develop new iron based catalysts.

Dendrimers belong to a well-recognized class of precise macromolecules with highly branched structure and globular shape that have been applied in several fields, one of the most important being the catalysis [16-18]. Their advantages in catalysis are unique, such as high dispersion, high loading level, high stability, good solubility, and controlled particle sizes and morphologies of the catalyst [19-21]. However, the industrial application of dendrimer-based catalysts has been restricted mainly because of the difficulty of their separation and recycling. Therefore, there is a widespread interest in the recent years in design and fabrication of these catalysts grown on solid supports to solve these problems. [22,23].

Different types of supporting materials, such as carbon, mesoporous silica, amorphous silica, magnetic nanoparticles, and titania have been used for the immobilization of dendrimer-based catalysts [24-28]. In particular, magnetic nanoparticles have received the considerable attention of researches due to their unique physical properties including high surface to volume ratio, low toxicity, and excellent thermal and chemical stabilities [29-32]. Most importantly, the magnetic nanoparticles-supported catalysts could be easily separated from the reaction medium by applying an external magnet without the necessity for filtration or centrifugation [33,34].

Until now, there are some reports about the preparation of dendrimer-supported transition metals using different solid supports and their applications as catalysts in various oxidation reactions. For example, Moghadam and his group have reported silica dendrimer-supported Mn, Ru, and Au catalysts in the oxidation of olefins and alcohols [35-37]. Also, other silica dendrimer-supported Mn catalysts for the oxidation of olefins have been reported [38,39]. Another research group, Hosseini-Monfared and co-workers, have developed dendrimer functionalized magnetic nanoparticles to immobilize a Mn-tetraamide macrocycle complex in order to prepare a heterogeneous catalyst for the oxidation of olefins [40]. In 2016, Vieira's group reported the synthesis of two Mo complexes immobilized on dendrimer functionalized silica, which was applied as catalysts for the oxidation of olefins [41]. All of these catalysts exhibited excellent activity and recyclability in the oxidation reactions.

So, with the background of the above reports and considering the significant benefits of dendrimer functionalized magnetic nanoparticles as solid support and iron complexes as active catalysts, we reported on the utilization of the dendrimer functionalized magnetite nanoparticles for immobilizing Fe(III)-salen complex to prepare a new heterogeneous catalyst. The synthesized catalyst was shown to be a high-performance and reusable catalyst for the selective oxidation of sulfides to sulfoxides using H_2O_2 (30% w/w) as oxidant in

aqueous medium at 50 °C. To the best of our knowledge, there was no report about the immobilization of iron complexes on the dendrimer functionalized magnetite nanoparticles for catalytic application purpose.

Experimental

The details of materials and methods section were reported in the supporting information.

Preparation of G0-Fe₃O₄-SiO₂

Silica-coated magnetic nanoparticles (Fe₃O₄-SiO₂) were synthesized according to a reported method [42]. To a homogeneous dispersed Fe₃O₄-SiO₂ (1 g) in 30 mL dry toluene, 2 mL of 3-aminopropyltriethoxysilane was added. Then the mixture was refluxed for 24 h under nitrogen atmosphere. The obtained product, nominated as G0-Fe₃O₄-SiO₂ was magnetically separated, washed thoroughly with ethanol, and dried at 80 °C overnight.

Preparation of dendrimer functionalized magnetic nanoparticles

1 g of the above synthesized G0-Fe₃O₄-SiO₂ was dispersed in 20 mL methanol under ultrasonication for 0.5 h. To this suspension, 0.42 g (5 mmol) of methyl acrylate was added and the mixture was stirred at room temperature for 24 h. The resulting product (G0.5-Fe₃O₄-SiO₂) was isolated by an external magnet, washed with methanol to effectively remove the unreacted reagents and then dried at 80 °C overnight. 1 g of the as-synthesized G0.5-Fe₃O₄-SiO₂ was suspended in 20 mL methanol, and after sonication for 0.5 h, 1.03 g of diethylenetriamine (10 mmol) was added and refluxed for 6 h under nitrogen atmosphere. After cooling to room temperature, the solid was separated using an external magnet, washed with methanol, and dried at 80 °C overnight to give G1-Fe₃O₄-SiO₂. G2-Fe₃O₄-SiO₂ was synthesized by repeating these two steps, the amount of reactants being adjusted as required.

Preparation of Fe₃O₄-SiO₂-dendrimer-Fe catalyst

2 mmol of salicylaldehyde was added to a suspension of 1 g of G2-Fe₃O₄-SiO₂ in 20 mL absolute ethanol and the reaction mixture was then refluxed for 24 h under nitrogen atmosphere. The resulting Schiff base immobilized on G2-Fe₃O₄-SiO₂ was separated by applying an external magnet, washed several times with ethanol and dichloromethane, and dried at 80 °C overnight. Complexation of Schiff base immobilized on G2-Fe₃O₄-SiO₂ in 20 ml of FeCl₃.6H₂O and 1 g of the synthesized Schiff base immobilized on G2-Fe₃O₄-SiO₂ in 20 mL methanol at room temperature over a period of 24 h. The obtained solid was magnetically separated, washed with methanol, and dried at 80 °C overnight. The resulting material was denoted as Fe₃O₄-SiO₂-dendrimer-Fe catalyst.

General procedure for the oxidation of sulfides to sulfoxides

A 10 mL round-bottom flask equipped with a magnetic stirrer was charged with sulfide (1 mmol), H_2O_2 (30% w/w, 2 mmol), Fe_3O_4 -SiO₂-dendrimer-Fe catalyst (0.1 g, 2 mol%), and water (3 mL). The mixture was stirred at 50 °C for an appropriate time. After completing the reaction, the product was extracted from the reaction mixture with chloroform, evaporated on the rotary evaporator at 40-50 °C and then analyzed by using gas chromatography (GC). During the reusability assessment, the catalyst was separated from the reaction mixture with an external magnet, washed several times with ethanol, dried in vacuum at 80 °C for 5 h, and then used for the next reaction.

Results and discussion

Synthesis and characterization of the catalyst

Dendrimer functionalized magnetite nanoparticles were prepared (Scheme 1) and used as support to anchor Fe(III)-salen complex to form Fe₃O₄-SiO₂-dendrimer-Fe catalyst, as seen in

Scheme 2. The amount of the metal content in the catalyst was measured by inductively couple plasma atomic emission spectroscopy (ICP-AES) analysis. The weight percentage of Fe was determined approximately to be 0.2 mmol/g by calculating the difference between the amount of Fe in G2-Fe₃O₄-SiO₂ and Fe₃O₄-SiO₂-dendrimer-Fe catalyst.



Scheme 1. Preparation of dendrimer functionalized magnetite nanoparticles.



Scheme 2. Preparation of Fe₃O₄-SiO₂-dendrimer-Fe catalyst.

FT-IR spectra of the products formed in each step of the synthesis of Fe_3O_4 -SiO₂dendrimer-Fe catalyst are shown in Figure 1. In all of the seven spectra, the bands around 800 and 1080 cm⁻¹ were attributed to the asymmetric and symmetric stretching vibration of Si-O-Si bond, and the band at about 590 cm⁻¹ was assigned to the Fe-O-Fe stretching vibration. Moreover, apart from the case of Fe₃O₄-SiO₂, the C-H stretching vibrations of CH₂ groups at about 2800-3000 cm⁻¹ were visible in all samples. The FT-IR spectra of G0.5-Fe₃O₄-SiO₂ and G1.5-Fe₃O₄-SiO₂ exhibited a band around 1735 cm⁻¹ which could be attributed to the stretching vibrations of the ester groups and was disappeared in the case of G1-Fe₃O₄-SiO₂ and G2-Fe₃O₄-SiO₂ following the amidation reaction [43]. This clearly confirmed the growth of the dendrimer on the surface of Fe₃O₄-SiO₂. Importantly, the FT-IR spectrum of Fe₃O₄-SiO₂, demonstrating that the structure of Fe₃O₄-SiO₂ and dendrimer was intact after the immobilization of Fe(III)-salen complex.

The growth of the dendrimer on the surface of Fe_3O_4 -SiO₂ was also confirmed by thermogravimetric analysis (TGA). The TGA curves in Figure 2 revealed that the organic moiety loaded on the surface of Fe_3O_4 -SiO₂ increased with each generation of growth.



Figure 1. FT-IR spectra of (a) Fe_3O_4 -SiO₂, (b) G0-Fe₃O₄-SiO₂, (c) G0.5-Fe₃O₄-SiO₂, (d) G1-Fe₃O₄-SiO₂, (e) G1.5-Fe₃O₄-SiO₂, (f) G2-Fe₃O₄-SiO₂, (g) Fe₃O₄-SiO₂-dendrimer-Fe catalyst.



Figure 2. TGA curves of (a) G0-Fe₃O₄-SiO₂, (b) G1-Fe₃O₄-SiO₂, (c) G2-Fe₃O₄-SiO₂.

Figure 3 exhibits the nitrogen adsorption-desorption isotherms for (a) G0-Fe₃O₄-SiO₂, (b) G1-Fe₃O₄-SiO₂, (c) G2-Fe₃O₄-SiO₂, and (d) Fe₃O₄-SiO₂-dendrimer-Fe catalyst. All four samples displayed typical type II isotherms. As the dendrimer generation increased, the surface area systematically decreased from 68 in G0-Fe₃O₄-SiO₂ to 63 and 58 m² g⁻¹ in G1-Fe₃O₄-SiO₂ and G2-Fe₃O₄-SiO₂, respectively. The surface area further decreased to 54 m² g⁻¹

for Fe_3O_4 -SiO₂-dendrimer-Fe catalyst. Such decreases may be due to the more loading of organic species on the surface of nanoparticles, indicating the successful immobilization of the dendrimer and Fe(III)-salen complex on the surface of Fe_3O_4 -SiO₂.



Figure 3. N₂ adsorption-desorption isotherms of (a) G0-Fe₃O₄-SiO₂, (b) G1-Fe₃O₄-SiO₂, (c) G2-Fe₃O₄-SiO₂, (d) Fe₃O₄-SiO₂-Dendrimer-Fe catalyst.

Energy dispersive X-ray spectroscopy (EDX) analysis was employed to check the elements presented in the prepared Fe_3O_4 -SiO₂-dendrimer-Fe catalyst. The EDX spectrum of the catalyst (Figure 4) consisted of different peaks for C, N, O, Fe, Si, and Cl confirming the successful formation of Fe_3O_4 -SiO₂-dendrimer-Fe catalyst. Furthermore, the elemental mapping of the catalyst demonstrated that these elements were distributed homogeneously in the texture of the catalyst (Figure 5).



Figure 4. EDX spectrum of Fe₃O₄-SiO₂-dendrimer-Fe catalyst.



Figure 5. Elemental mapping of C, N, O, Fe, Si, and Cl.

Additionally, X-ray photoelectron spectroscopy (XPS) analysis on Fe_3O_4 -SiO₂dendrimer-Fe catalyst exhibited the characteristic peaks of C 1s, N 1s, O 1s, Cl 2p, Fe 2P, Si 2s, and Si 2p, as shown by the survey spectrum in Figure 6a. The high resolution XPS spectrum of Fe 2p in Figure 6b revealed four peaks, among which the peaks with binding energies of 710.1 (Fe, $2p_{3/2}$) and 723.7 eV (Fe, $2p_{1/2}$) could be indexed to the Fe (II) oxidation state, whereas the peaks at 712.4 (Fe, $2p_{3/2}$) and 725.3 eV (Fe, $2p_{1/2}$) were assigned to the Fe (III) oxidation state [44]. The results showed that the Fe ions had +3 and +2 oxidation states in Fe₃O₄-SiO₂-dendrimer-Fe catalyst.



Figure 6. (a) XPS survey spectrum of Fe_3O_4 -SiO₂-dendrimer-Fe catalyst and (b) corresponding high resolution spectrum of Fe 2p.

The crystalline structures of Fe_3O_4 -SiO₂ and Fe_3O_4 -SiO₂-dendrimer-Fe catalyst were disclosed by X-ray diffraction (XRD) patterns as presented in Figure 7. The diffraction peaks for Fe_3O_4 at 30° (220), 35° (311), 43° (400), 53° (422), 56° (511), and 62° (440) were indexed to the face-centered cubic structure of Fe_3O_4 (JCPDS Card no. 19-0629). Also, no

remarkable variation in the pattern of Fe_3O_4 -SiO₂-dendrimer-Fe catalyst suggested that the crystalline structure of Fe_3O_4 did not destroyed during the synthesis of the catalyst.



Figure 7. XRD patterns of (a) Fe₃O₄-SiO₂ and (b) Fe₃O₄-SiO₂-dendrimer-Fe catalyst.

The structures and surface morphologies of Fe_3O_4 -SiO₂ and Fe_3O_4 -SiO₂-dendrimer-Fe catalyst were investigated by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The SEM images exhibited that both samples presented uniform spherical-shape morphology (Figures 8a and 8b). The TEM image of Fe_3O_4 -SiO₂ shown in Figure 8c further confirmed that Fe_3O_4 -SiO₂ consisted of spherical nanoparticles and a coreshell structure, in which the condensation of SiO₂ on the surfaces of Fe_3O_4 cores results in microspheres with dark-colored Fe_3O_4 cores and gray-colored SiO₂ shells. The magnetite nanoparticles kept their core-shell structure after the immobilization of the dendrimer and Fe(III)- salen complex (Figure 8d).



Figure 8. SEM images of (a) Fe_3O_4 -SiO₂ and (b) Fe_3O_4 -SiO₂-dendrimer-Fe catalyst and TEM images of (c) Fe_3O_4 -SiO₂ and (d) Fe_3O_4 -SiO₂-dendrimer-Fe catalyst.

Magnetization curves of Fe_3O_4 -SiO₂ and Fe_3O_4 -SiO₂-dendrimer-Fe catalyst at room temperature are given in Figure 9. As seen, no remanence or coercivity was detected in these curves, suggesting their superparamagnetic character. The saturation magnetization of Fe_3O_4 -SiO₂-dendrimer-Fe catalyst was 32 emu g⁻¹, smaller than that of Fe_3O_4 -SiO₂ (47 emu g⁻¹) owing to the decrease in Fe_3O_4 content of the catalyst. Even with this reduction in the saturation magnetization, Fe_3O_4 -SiO₂-dendrimer-Fe catalyst could be rapidly separated from the mixture within 10 s by applying an external magnet (inset of Figure 9).



Figure 9. Room temperature magnetization of (a) Fe₃O₄-SiO₂ and (b) Fe₃O₄-SiO₂-dendrimer-Fe catalyst.

Catalytic performance of the catalyst in the selective oxidation of sulfides

After the detailed characterization of Fe₃O₄-SiO₂-dendrimer-Fe catalyst, its catalytic activity was checked in the oxidation of sulfides. Methyl phenyl sulfide was chosen as a standard benchmark reactant to investigate the influence of various parameters on the reaction and the results are shown in Table 1. The influence of the catalyst amount was initially explored on the model reaction using H_2O_2 as oxidant at 50 °C in water. Different amounts of catalyst between 1-4 mol% were examined for the reaction (Table 1, entries 1-3), and 2 mol % of the catalyst was found to be the most suitable amount. Note that less than 30% conversions were achieved when the reactions were carried out without any catalyst and in the presence of Fe₃O₄-SiO₂ and G2-Fe₃O₄-SiO₂ (Table 1, entries 4-6). The results confirmed the poor catalytic role of these materials in this oxidation process. Next, the influence of H_2O_2 to sulfide molar ratio on the model oxidation reaction was investigated (Table 1, 7-9) which 2:1 molar ratio was found to be the best choice. The influence of reaction temperature on the product yield was also studied and reactions were conducted at oil bath temperatures of 30, 50, and 70 °C. The best result was obtained at 50 °C, while

decreasing the temperature to 30 °C led to a significant decrease in the product yield (Table 1, entry 10). On the other hand, further increasing the temperature to 70 °C did not lead to significant improvements (Table 1, entry 11). Under these conditions, the effect of solvent on the model oxidation reaction was monitored. It was observed that the reaction proceeded well in different solvents such as toluene, ethanol, acetonitrile, dichloromethane, and water, and water as a green solvent was preferred (Table 1, entries 12-15).

Table 1. Optimization	of the oxidation	of methyl phenyl s	sulfide. ^a
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	SS_	<	Catalyst	•	s +		S
		Н	2 <mark>0</mark> 2 (aq. 30%) Solvent			В	
Entry	Catalyst	H_2O_2	Solvent	Temperature	Time	Conversion	Selectivity
	(mol%)	(mmol)		(°C)	(h)	$(\%)^{b}$	to A $(\%)^{c}$
1	1	2	H ₂ O	50	2	67	93
2	2	2	H ₂ O	50	2	100	100
3	4	2	H ₂ O	50	2	100	100
4	-	2	H_2O	50	8	14	93
5	Fe ₃ O ₄ -SiO ₂	2	H ₂ O	50	8	24	92
	(30 mg)						
6	G2-Fe ₃ O ₄ -	2	H_2O	50	8	21	97
	SiO_2						
	(30 mg)						
7	2	1	H ₂ O	50	4	86	92
8	2	3	H ₂ O	50	2	100	100
9	2	4	H_2O	50	2	100	100
10	2	2	H ₂ O	30	2	93	95
11	2	2	H_2O	70	2	100	100

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12	2	2	toluene	50	2	96	97
13	2	2	EtOH	50	2	100	100
14	2	2	CH ₃ CN	50	2	100	100
15	2	2	CH ₂ Cl ₂	50	2	100	100

[a] Reaction conditions: methyl phenyl sulfide (1 mmol), solvent (3 mL).

[b] Conversions were determined by GC using an internal standard technique and are based on sulfides.

[c] Selectivity to sulfoxide = [sulfoxide %/(sulfoxide %+Sulfone %)]×100.

To exhibit the general applicability of this protocol, Fe₃O₄-SiO₂-dendrimer-Fe catalyst was further utilized for the selective oxidation of various sulfides to the corresponding sulfoxides (Table 2). In all cases, the oxidations were completed within time periods between 2-6 h and gave the products in excellent yields. Notably, the reactions were observed to stop completely at the sulfoxides stage, even on increasing the reaction time. For exploring the electronic effect on the reaction performance, the para- substituted methyl phenyl sulfides were tested. The presence of electron-donating bromide group enhanced the reaction in comparison with electron-withdrawing nitro group, suggesting that electronic natures of the sulfides affected the reaction rate (Table 2, entries 3 and 4). In a similar way, less reactive substrates such as diaryl sulfides were successfully oxidized to the corresponding sulfoxides with high yields and selectivities (Table 2, entries 5-7). Interestingly, the oxidation of more challenging sulfides with other sensitive functional groups such as hydroxyl and olefin took place without affecting the functional groups, indicating a high chemoselectivity (Table 2, entries 6 and 8). To further extend the scope of this catalytic system, aliphatic sulfides were also tested. Interestingly, this catalytic system also proved applicable to the oxidation of aliphatic sulfides, and good to excellent yields of corresponding sulfoxides were achieved (Table 2, entries 9 and 10).

Entry	Sulfide	Time (h)	Sulfoxide (%) ^b	Selectivity (%) ^c
1	S S	2	100	100
2	S S	2.5	100	96
3	Br	4.5	98	93
4	O ₂ N	6	93	91
5	S S	6	87	92
6	но он	4	>99	97
7	s S	6	96	95
8	S √S	2	>99	98
9	∕s	4	96	95
10	\sim s \sim	4.5	95	82

Table 2. Oxidation of various sulfides to the corresponding sulfoxides catalyzed by Fe_3O_4 -SiO₂-dendrimer-Fe catalyst^a.

[b] Conversions were determined by GC using an internal standard technique and are based on sulfides.

[[]a] Reaction conditions: sulfide (1 mmol), 30% H_2O_2 (2 mmol), catalyst (2 mol%), and H_2O (3 mL) at 50 (°C).

[c] Selectivity to sulfoxide = [sulfoxide %/(sulfoxide %+Sulfone %)]×100.

We also compared the results achieved in this work with various recoverable catalysts that have been reported in literature for the oxidation of methyl phenyl sulfide. The comparison results summarized in Table 3 indicated that the catalyst was comparable or better catalyst with respect to reaction condition, time, and yield than other catalytic systems. Furthermore, like the catalysts immobilized on magnetic nanoparticles, the present catalyst could be easily separated from the reaction mixture with the aid of an external magnetic field.

Entry	Catalyst	Reaction conditions	Conversion	Ref
			(%)	
1	Fe ₃ O ₄ -SiO ₂ -dendrimer-Fe	methyl phenyl sulfide (1 mmol),	100	This work
	(2 mol%)	H_2O (3 mL), $H_2O_2(2 \text{ mmol})$, T =		
		50 °C, t = 2 h		
2	Fe ₃ O ₄ @SiO ₂ -APTES-FeL	methyl phenyl sulfide (1 mmol),	>99	[45]
	(2 mol%)	EtOH (1 mL), $H_2O_2(3 \text{ equiv.})$,		
		RT, $t = 2 h$		
3	WOx/SBA-15(20)	methyl phenyl sulfide (2 mmol),	98	[46]
	(0.05 g)	CH ₃ OH/CH ₂ Cl ₂ (1:1, 10 mL),		
		TBHP (equiv.), RT, t = 10 h		
4	SBA-15/NH ₂ -FeQ ₃	methyl phenyl sulfide (0.5 mmol),	87	[2]
	(5 mol%)	H_2O (1 mL), $H_2O_2(1.5$ mmol),		
		RT, t = 3 h		
5	Fe ₃ O ₄ @SiO ₂ -APTES	methyl phenyl sulfide (1 mmol),	92	[6]
	(Fe(acac)2)	EtOH (3 mL), H ₂ O ₂ (1.5 equiv.),		
	(2 mol%)	RT, t = 2 h		

Recycling of the catalyst

The recyclability of Fe₃O₄-SiO₂-dendrimer-Fe catalyst was investigated in the oxidation of methyl phenyl sulfide under the optimized reaction conditions. At the end of each reaction, the catalyst was readily separated from the reaction mixture by an external magnet, rinsed with ethanol, dried in vacuum, and reused for subsequent reactions. As shown in Figure 10, both the activity and selectivity of the catalyst remained unchanged even after 5 cycles. Additionally, the stability of the catalyst was confirmed by FT-IR and TEM analyses of the catalyst after five cycles. The similarity of the FT-IR spectrum (Figure S1) and the TEM image (Figure S2) of fresh Fe₃O₄-SiO₂-dendrimer-Fe catalyst and after five cycles clearly demonstrated that the structure and morphology of the catalyst remained unaltered after five recoveries.



Figure 10. Reusability of Fe₃O₄-SiO₂-dendrimer-Fe catalyst.

Conclusion

In conclusion, we have designed and synthesized a novel heterogeneous catalyst by the immobilization of Fe(III)-salen complex on dendrimer functionalized magnetic nanoparticles. The obtained catalyst revealed excellent activity in green and selective oxidation of a variety

of sulfides to sulfoxides. Furthermore, the catalyst could be recovered and reused for at least five times without any decrease in the catalytic activity and selectivity. Because of the magnetic nature of the catalyst, it could be separated from the reaction mixture easily by applying an external magnet, which eliminated the filtration and centrifugation process for catalyst separation after completion of the reaction.

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Conflict of interest

The authors declare no conflict of interest.

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Highlights

A novel nanohybrid material based on salen iron complex immobilized on dendrimer functionalized magnetite nanoparticles was synthesized.

The synthesized nanohybrid material was successfully applied as a recyclable catalyst for the oxidation of various sulfides.

The catalyst could be separated easily by applying an external magnet and recycled up to five cycles without significant decrease in catalytic activity and selectivity.

Conflict of interest

The authors declare no conflict of interest.

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Declaration of interests

 \boxtimes 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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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