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Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4]: A new magnetic solid acid nanocatalyst for the synthesis of benzoxazole derivatives

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ABSTRACT

A novel magnetite nanoparticle-based heterogeneous acidic catalyst [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4] was successfully prepared and characterized by SEM, EDX, TGA, VSM and FT-IR techniques. The magnetically retrievable and sustainable catalyst was investigated in the reaction of aldehyde and o-aminophenol for the synthesis of benzoxazoles. The reactions occurred in water and produced the corresponding products in high yields. The catalyst could be readily separated by an external magnet and showed excellent reusability without significant loss of its activity.

Keywords: *Magnetic nanoparticles, Benzoxazoles, Solid acid catalyst, Reusability.*

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1. Introduction

Recently, magnetite nanoparticles (MNPs) have attracted a great deal of interest because of their various fields of applications such as electronics, physics, material science, analysis, medicine and catalyst [1-9]. Due to simple recovery and coupling with organic and inorganic compounds, MNPs have been widely used as the core of the catalyst support in organic transformation [10]. On the other hand, solid acid materials have been used as both the catalyst and catalyst support in organic reactions due to non-toxicity, non-corrosiveness, high surface area, ease of handling, enhanced reaction rates, thermal stability, and reusability. In recent years, the combination of the properties of MNPs and solid acid catalysts within a single material has emerged as a powerful tool for the recovery of the solid acid catalyst in organic synthesis [11-15].

Five- and six-membered rings are important classes of heterocyclic compounds with many biological activities. Benzoxazoles have revealed antibacterial, antihistamic, antitumor, anti-HIV, and antihypertensive properties [16-20]. In addition, benzoxazolyl alanines act simultaneously as the coordinating and reporting unit via fluorescence changes. These compounds were prepared with a furan ring at position 2 substituted with different (hetero) aryl substituents in order to tune photophysical and chemosensory properties of the resulting compounds [21]. These compounds also have applications in various dyes due to their fluorescent nature [22]. Several publications have been reported for the preparation of these heterocycles including the condensation of carboxylic acids [23], acid chlorides [24], esters [25] and aldehydes [26] with o-substituted amino aromatics. In the latter reactions, various oxidants such as nano SnO_2 [27], nano ZnO [28] and CdO nanoparticles [29] have been used. However, some of these methods suffer from disadvantages such as extended reaction times, unsatisfactory yields, safety problems, cost of the reagents and tedious work-up.

In continuation of our research endeavors to develop sustainable protocols and applications of nano-catalysts [8-10, 30], herein, we report the preparation, characterization, and the use of [nano-Fe_3O_4@SiO_2@ $(CH_2)_3$NPPC-SO_3H][HSO_4] or MNP@PPC-SO_3H as a novel solid acid catalyst for the synthesis of benzoxazoles by reaction of aryl aldehydes and o-aminophenols (Scheme 1).

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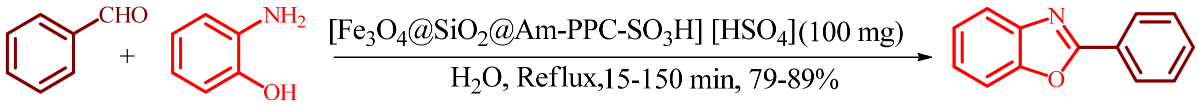


Scheme 1. Synthesis of benzoxazole derivatives using MNPs catalyst.

2. Experimental

2.1. General

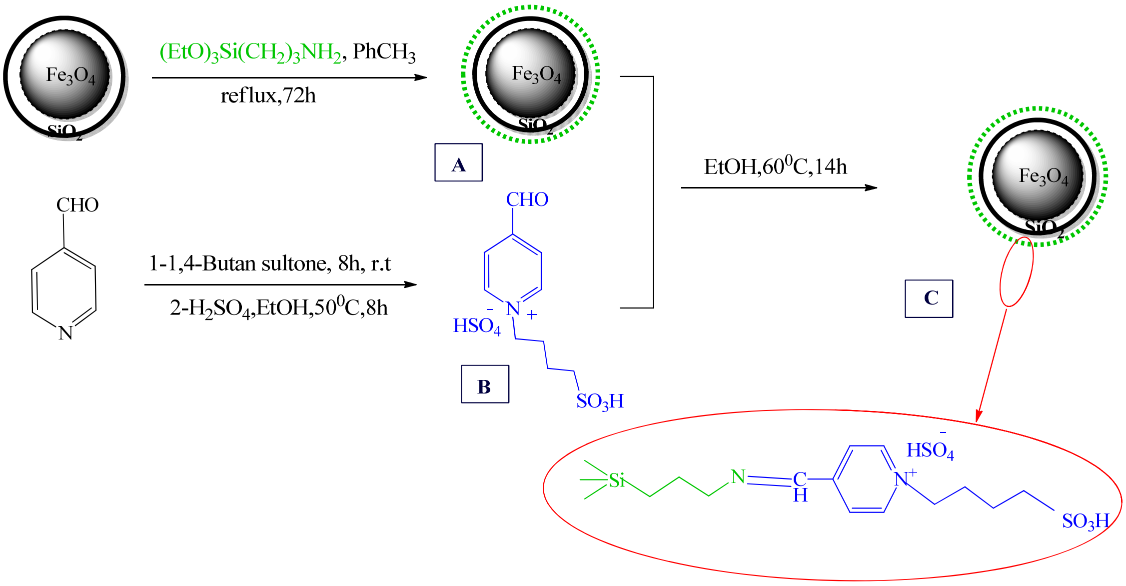
All chemicals were commercial products. Fe_3O_4 and $Fe_3O_4@SiO_2$ were prepared according to reported methods [31-32]. All reactions were monitored by TLC and all yields refer to isolated products. Melting points were determined using a Stuart scientific apparatus. SEM images were obtained from a Zeiss-Vp-500 instrument. IR spectra were recorded on a Perkin Elmer IR- Rx1 spectrophotometer. TGA analysis was performed under nitrogen with a heating rate of 10 °C/min using a Perkin Elmer, Pyris1. Magnetism analysis was performed on a vibrating sample magnetometer (4 in., Daghigh Meghnatis Kashan Company, Kashan, Iran) at room temperature. SEM-EDX analyses were carried out using a Philips XL30 instrument.

2.2. Preparation of [$Fe_3O_4@SiO_2@Am$-PPC-SO_3H] [HSO_4]

For the synthesis of $Fe_3O_4@SiO_2@Am$ (compound A), $Fe_3O_4@SiO_2$ (1 g) and (3-aminopropyl) triethoxysilane (1 mL) in 5 mL of dry toluene were refluxed at 110 °C for 72 h. The solid material was filtered, washed with toluene, ethanol and diethyl ether, and dried under reduced pressure. For the synthesis of 1-pentyl-1-pyridine-4-carboxaldehyde sulfonate (PPC-SO_3H, compound B), 1,4-butane sultone (0.285 g, 2.1 mmol) was added dropwise to the 4-pyridinecarboxaldehyde (0.214 g, 2 mmol) and the mixture was stirred at room temperature for 8 h and then a solution of H_2SO_4 (2 mL) and ethanol (5 mL) was added dropwise and the reaction mixture was refluxed at 50 °C for 8 h. After cooling to room temperature, the viscose materials were filtered off, washed with acetone and dried in a vacuum. Then, to synthesize $Fe_3O_4@SiO_2@Am$-PPC-SO_3H nanoparticles, a mixture of 1 mmol compound A in 10 mL of ethanol was added to 1 mmol of compound B, and the resulting mixture was refluxed at 60 °C for 14 h. Finally, the 4-pyridinecarboxaldehyde with the sulfonic acid tag on silica coated Fe_3O_4 magnetic nano particles [$Fe_3O_4@SiO_2@Am$-PPC-SO_3H] [HSO_4] was obtained after filtering, washing with acetone and drying.

2.3. General procedure for the synthesis of 2-substituted benzoxazoles

A mixture of aldehyde (1 mmol), *o*-aminophenol (1 mmol) and the catalytic amount of [$Fe_3O_4@SiO_2@Am$-PPC-SO_3H] [HSO_4] (100 mg) was stirred in water (5 mL) at reflux conditions. After completion of the reaction (monitored by TLC, eluent; n-hexane: EtOAc, 4:1), the catalyst was separated by using an external magnet. After evaporation of the solvent, the crude products were recrystallized from ethanol-water (10:1) to give pure products.



Scheme 2. Preparation of [$Fe_3O_4@SiO_2@Am$-PPC-SO_3H] [HSO_4].

3. Results and Discussion

The FT-IR spectrum of MNP@PPC-SO_3H (Fig. 1) shows characteristic peaks at 2926, 1627, 1505 1109 and 793 cm^{-1} due to stretching vibrations of C-H (aromatic rings and linker moiety), C=C, C=N, and S-O_3H. The absorption peak at 1109 cm^{-1} is assigned to the asymmetric stretching vibration of Si–O–Si. Additionally, the absorption band at 3427 cm^{-1} is related to the stretching vibration of O–H in the SO_3H and Si–OH groups. Also, the vibration of Fe-O is observed at 504 cm^{-1}.

In order to investigate the particle size and morphology, the results of scanning electron microscopy (SEM) of the catalysts are represented (Fig. 2). The SEM image of MNP@PPC-SO_3H shows spherical nanoparticles with the size of less than 100 nm.

To investigate the amount of weight change of nano magnetic catalyst, TGA technique was used (Fig. 3). The first mass loss of 5% below 200 °C is related to desorption of water and organic solvents from the catalyst surface. The second exothermic loss in weight (25 % w/w) at 250-650 °C can be ascribed to the thermal decomposition of the organic materials and confirmed that the organic groups are covalently bound on the surface of MNPs catalyst.

The Energy-dispersive X-ray spectroscopy (EDX) of MNP@PPC-SO_3H is shown in Fig. 4. The result shows that the main elements in the magnetite nanoparticles are O (37.7% wt), C (24.6% wt), N (12.0% wt), Si (10.6% wt), Fe (9.5% wt) and S (5.5% wt).

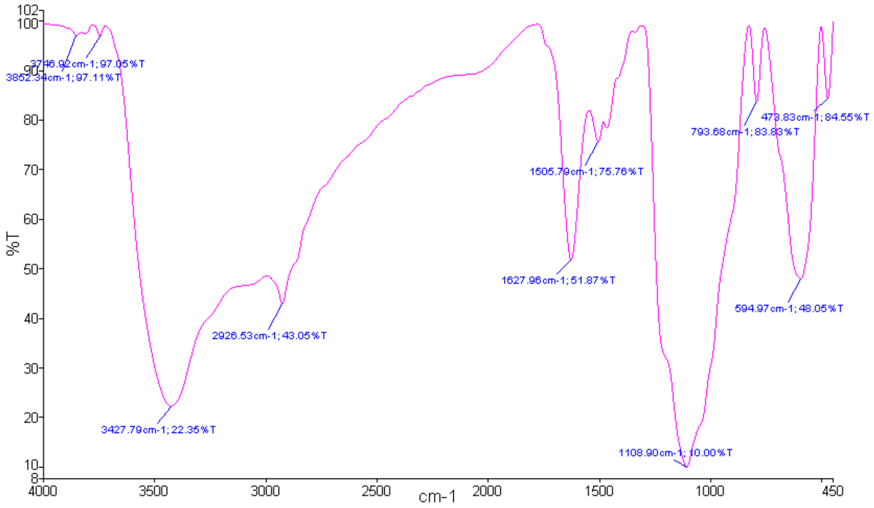


Fig. 1. The IR spectrum of nano [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4].

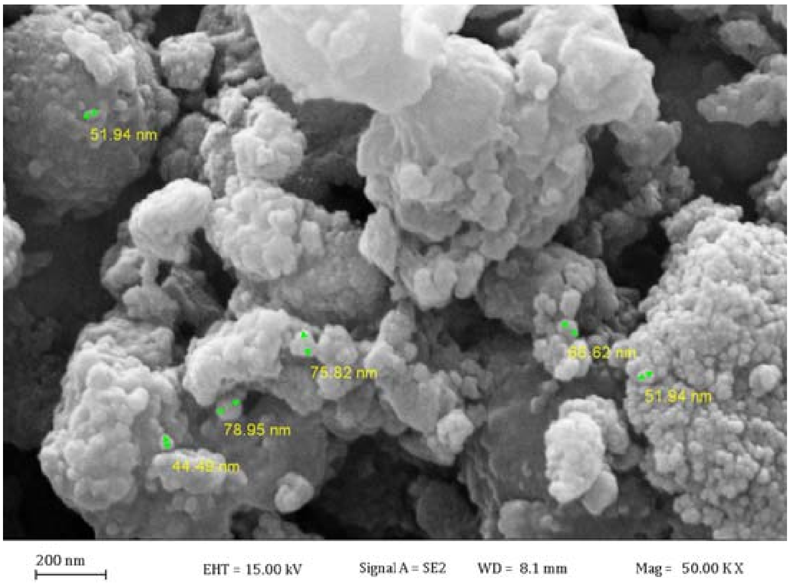


Fig. 2. SEM image of the [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4]

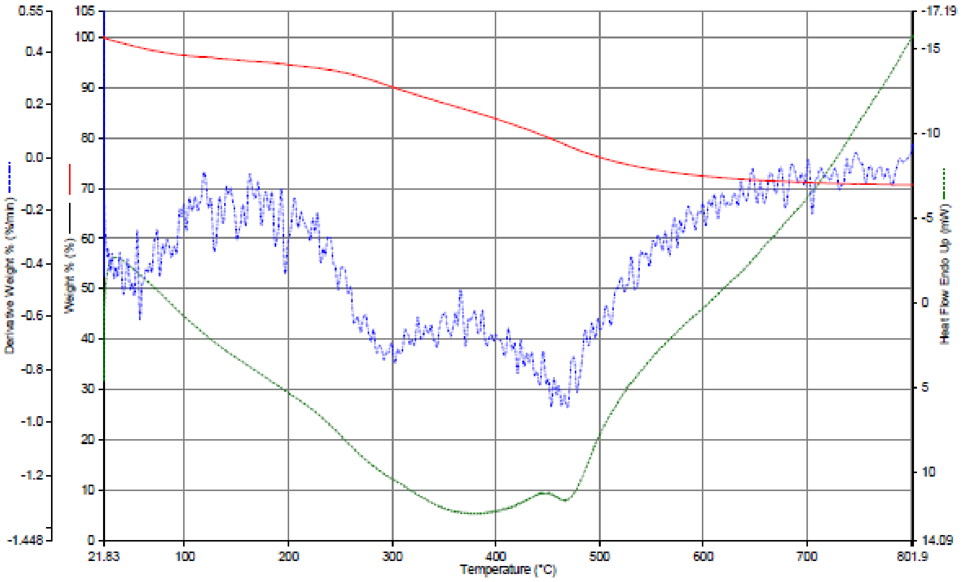
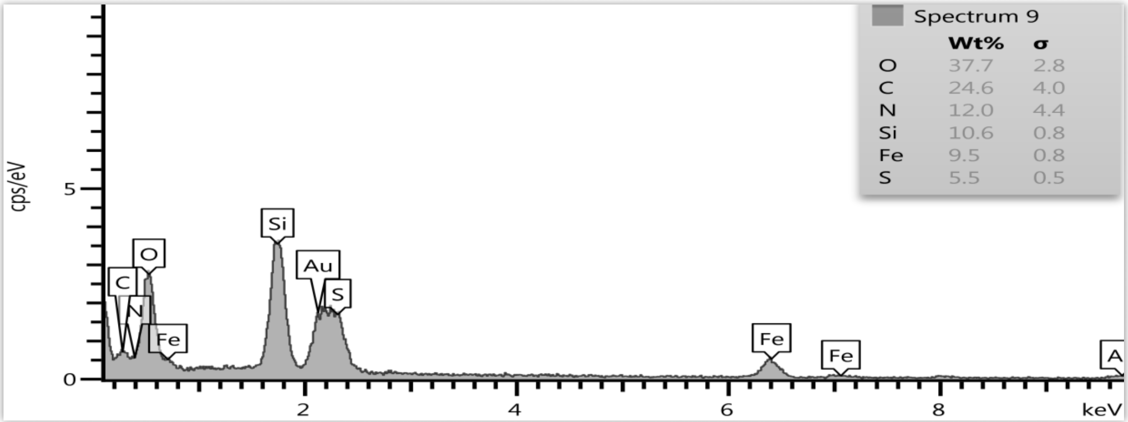


Fig. 3. TGA Analysis of [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4] as a solid acid catalyst.



Spectrum 9

	Wt%	σ
O	37.7	2.8
C	24.6	4.0
N	12.0	4.4
Si	10.6	0.8
Fe	9.5	0.8
S	5.5	0.5

Fig.4. The energy-dispersive X-ray spectroscopy of [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4].

Magnetic measurements of the catalyst were carried out at room temperature using a vibrating sample magnetometer (VSM). The VSM technique is used to measure the magnetization value of magnetic particles under applied magnetic field. The obtained curves of Fe_3O_4 and [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4] at room temperature are depicted (Fig. 5). The maximum saturation magnetizations were 60 and 16 emu/g for Fe_3O_4 and magnetic nanocatalyst respectively. These results show that even with the lower magnetic saturation, the catalyst can still be effectively separated from the solution by an external magnet. In addition, the magnetic separation ability is further investigated in reaction through a separation process by applying an external magnet near the reaction mixture vessel. The immiscible droplets were attracted towards the magnet within a short period of time. Also, according to acid−base titration the number of H^+ site of the MNPS was 0.87 mmol.g^{-1}. The performance of [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4] was surveyed for the synthesis of benzoxazole derivatives (Scheme 1). Initially, for optimization of reaction conditions and the amount of the catalyst, the reaction of benzaldehyde with *o*-aminophenol was carried out as the model reaction. The effect of the amounts of the catalyst in the range of 0.05–0.2 g of catalyst relative to benzaldehyde was examined and results are shown in Table 1. As shown in Table 1, the reaction progress was increased up to 0.1 g by increasing the amount of catalyst and more increase in amount decreased the conversion (entries 1–5). The effect of solvent was also investigated by performing the model reaction in the presence of 100 mg catalyst in various solvents and under solvent-free conditions (entries 6–9).

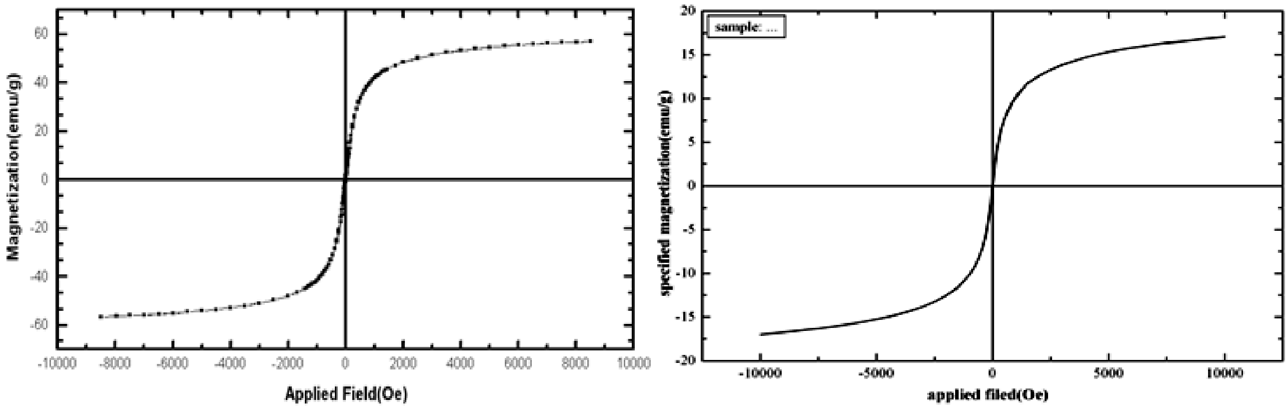


Fig. 5. VSM magnetization curve of the Fe_3O_4 (upper) and MNPs catalyst (lower).

Table 1. Optimization of reaction conditions for the synthesis of benzoxazoles in the presence of $[Fe_3O_4@SiO_2@Am\text{-}PPC\text{-}SO_3H][HSO_4]$.

No.	Catalyst	Solvent	Catalyst amount (mg)	Condition	Time (min)	Yield (%)[a]
1	MNP@PPC-SO_3H	H_2O	50	reflux	100	45
2	MNP@PPC-SO_3H	H_2O	70	reflux	100	60
3	MNP@PPC-SO_3H	H_2O	100	reflux	45	87
4	MNP@PPC-SO_3H	H_2O	150	reflux	45	82
5	MNP@PPC-SO_3H	H_2O	200	reflux	40	79
6	MNP@PPC-SO_3H	CH_2Cl_2	100	reflux	45	60
7	MNP@PPC-SO_3H	CH_3CN	100	reflux	45	65
8	MNP@PPC-SO_3H	MeOH	100	reflux	45	75
9	MNP@PPC-SO_3H	-	100	reflux	45	60
10	MNP@PPC-SO_3H	H_2O	100	r.t.	120	50
11	PPC-SO_3H	H_2O	100	reflux	45	60
12	None	H_2O	-	reflux	120	trace

[a]Isolated yields.

The results clearly showed that water was the best solvent among those tested. To show efficiency of the support, the model reaction was examined in the presence of the pure 1-pentyl-1-pyridine-4-carboxaldehyde sulfonate (PPC-SO_3H) and according to the obtained result 60% yield of the product was obtained after 45 min, the main disadvantages of this catalyst was the difficulty in the reusability and separating of the catalyst (entry 11). The reaction was also performed at room temperature and results showed only 50% yield of the product after 2 h (entry 10). In a blank reaction (without the catalyst), only trace amounts of the product were achieved after 120 min (entry 12). The scope and generality of this methodology are illustrated with respect to the reaction of various types of aldehydes with *o*-aminophenols and results are summarized in Table 2. According to the results of optimization experiments, the reaction was carried out in the presence of 100 mg magnetic nanocatalyst in H_2O under reflux conditions and the corresponding benzoxazoles were obtained in high yields (Table 2). Various types of aldehydes with both electron-donating and electron-withdrawing substituents were reacted under the same reaction conditions and the better results were observed for aldehydes containing an electron-withdrawing substituent. Steric hindrance of substrate is an important factor in the yield and time of the reaction. For instance, the time and yield of the reaction for 4-chlorobenzaldehyde and 2-chlorobenzaldehyde show this fact. 1-Naphthaldehyde and 4-Vinylbenzaldehyde were also reacted with 2-aminophenol in the same reaction conditions to afford the corresponding products in high yields (entries 15-16).

Table 2. Formation of 2-Arylbenzoxazoles catalyzed by [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4].

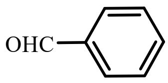
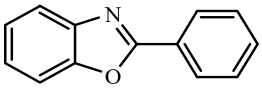
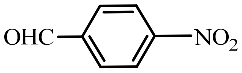
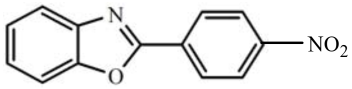
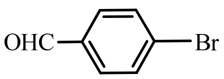
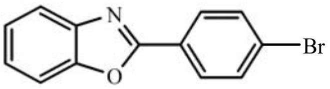
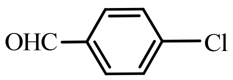
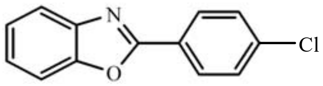
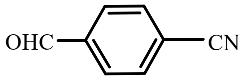
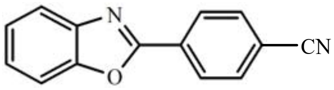
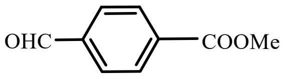
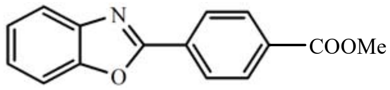
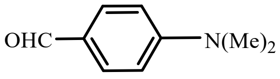
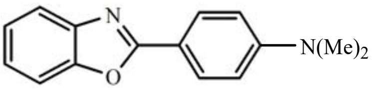
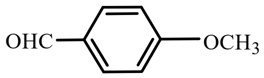
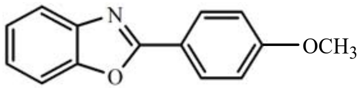
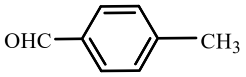
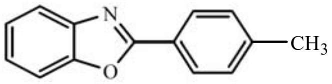
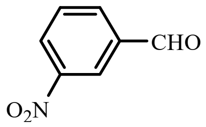
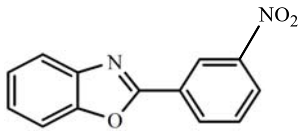
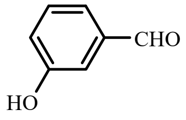
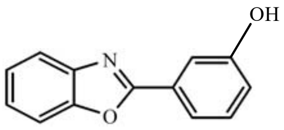
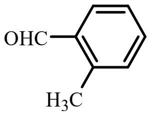
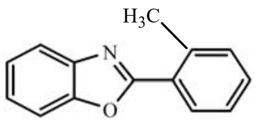
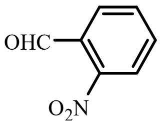
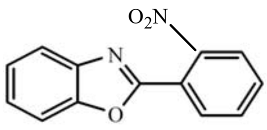
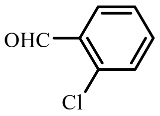
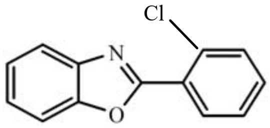
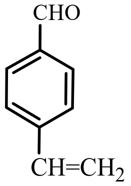
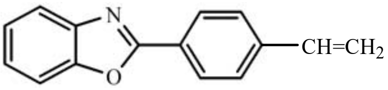
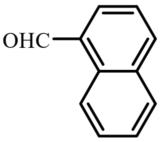
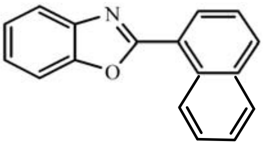
No.	Substrate	Product	Time (min)	Yield (%)[a]	m.p. (°C)	Ref.
1			45	87	100-101	[33]
2			15	86	265-267	[33]
3			30	85	156-158	[25]
4			25	84	147-149	[33]
5			20	82	202-204	-
6			25	80	197-199	-
7			135	87	185-187	[34]
8			150	89	99-100	[33]
9			100	84	114-116	[33]
10			35	83	Oil	-
11			120	81	172-174	[34]
12			130	80	64–66	-
13			45	82	Oil	-

Table 2 (*Continued*).

14			120	79	63-65	[34]
15			135	82	82-84	-
16			110	85	104-106	-

[a]Isolated yields.

The workup and catalyst recovery are very simple. All of the reactions have very high selectivity toward corresponding benzoxazoles. After completion of the reaction, the catalyst was separated using an external magnet and was washed with acetone. The crude product was recrystallized by EtOH to obtain the pure product.

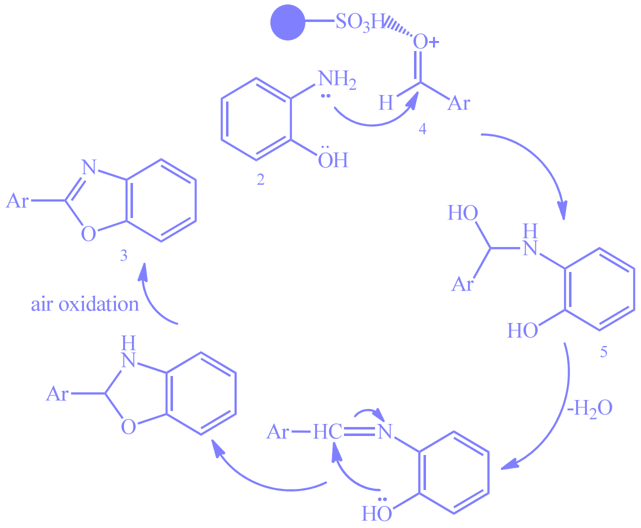
The efficiency of [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4] was also compared with other similar heterogeneous catalytic systems in the same reactions (Table 3). The obtained results indicate the superiority of the present catalyst in terms of the catalyst amount, yield or reaction times.

A possible mechanism for the synthesis of benzoxazole derivatives has been proposed in Scheme 3. First, [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4] as a magnetic solid acid catalyst activates the carbonyl group of the aromatic aldehyde (1) to provide intermediate (4). The nucleophilic attack of o-aminophenols (2) on the intermediate (4) was carried out to form the intermediate (5). Then, the hydroxyl group performs intramolecular nucleophilic attack on the imine bond and gives the benzoxazole derivatives (3) via air oxidation.

Table 3. Comparison of the catalytic activity of MNP@PPC-SO_3H with other catalysts in the synthesis of 2-phenylbenzoxazole.

No.	Catalyst	Amount of the catalyst	Solvent/ Condition	Time	Yield (%)[a]	Ref.
1	Tertbutyl hypochlorite	2 mmol	MeCN	2 h	92	[35]
2	Glycerol	5 ml	MeOH/90 °C	4 h	90	[36]
3	Diethyl bromophoshonate	2 mmol	MeCN	2.5 h	85	[35]
4	Cu- NPs	10 mol%	MeOH/O_2/100 °C	3 h	90	[37]
5	$TiCl_3OTf$	10 mol%	ethanol	130 min	80	[26]
6	Polystyrene(iodosodiacetate)	1.4 mmol	MeCN	1.5 h	71	[33]
7	IBX/MS	0.56/0.1 g	EtOAc	18 h	73	[38]
8	DDQ	0. 25g	CH_2Cl_2/45 °C	12.5 h	93	[39]
9	Darco KB	1g	Xylene /O_2/120 °C	4 h	78	[40]
10	PPC-SO_3H @MNP	0. 1g	H_2O	45 min	87	This work

[a]Isolated yields.
[b]2-ethylbenzoxazole.



Scheme 3. Plausible mechanism for the synthesis of benzoxazole derivatives.

To study the reusability of the MNP@PPC-SO_3H, the recovered catalyst from the model reaction was washed with EtOH and dried in an oven at 110 °C for 2 h. The recovered catalyst was reused in the same reaction four times. The reaction proceeded smoothly with a yield of 82– 85%. Although a serious problem of solid support acid catalysts is migration of some of the active sites from the solid support to the liquid phase during the reaction process, the obtained results indicate that the catalyst does not have an appreciable change in its activity and shows only a slight decrease in the yield after the first run.

4. Conclusions

The present work describes [Fe_3O_4@SiO_2@Am-PPC-SO_3H] [HSO_4] as a promising nano-catalyst for the synthesis of benzoxazoles under mild conditions in high yields. This magnetic catalyst is separated by an external magnet. In addition, the catalyst is reusable for several cycles without any significant loss in catalytic activity. Further applications of this catalyst are under investigation in our laboratory.

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