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# Nano-Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub>-supported boron sulfonic acid as a novel magnetically heterogeneous catalyst for the synthesis of pyrano coumarins†

Mahnaz Farahi,<sup>ID</sup>\* Bahador Karami,<sup>ID</sup> Raziye Keshavarz and Foroogh Khosravian

In this study, a novel magnetically heterogeneous catalyst based on the immobilization of boron sulfonic acid onto Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub> nanoparticles (Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub>-BSA) is reported. Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub>-BSA was characterized via FT-IR, X-ray diffraction patterns (XRD), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and vibrating sample magnetometer (VSM) analysis. The performance ability of this catalyst including acid sites was evaluated for the synthesis of pyrano coumarins under solvent-free conditions with high yields. Thermal stability of the catalyst and its easy separation by a magnetic field make this catalyst a good heterogeneous system and a useful alternative to other heterogeneous catalysts.

## Introduction

Supported heterogeneous catalysts as environmentally friendly materials play a pivotal role in modern science and technology, in particular, in the organic synthesis area.<sup>1–3</sup> Because of the many advantages of catalyst immobilization on solid supports, including easy handling, low solubility, increasing selectivity of the reactions, and non-toxicity, it is a technique that is widely used.<sup>4</sup> Nanostructure supports are also advantageous because they exhibit higher activity and selectivity than their corresponding bulk materials.<sup>5–8</sup> As the diameter of the particle decreases to the nanometer scale, the external surface area becomes available for chemical transformations.<sup>9</sup> Recent studies show that magnetite (Fe<sub>3</sub>O<sub>4</sub>) nanoparticles have unique properties such as simple isolation from the reaction mixture using an external magnetic field, high surface area, thermal stability, low cost, their potential to immobilize functional groups, and excellent recyclability, which make them useful supports to prepare reusable heterogeneous catalysts.<sup>10–12</sup> A protective shell of silica as a coating can be formed on the surface of Fe<sub>3</sub>O<sub>4</sub> nanoparticles to prevent them from oxidizing in an air atmosphere, provide simple surface functionalization, and enable aggregation between particles.<sup>13,14</sup>

Boron sulfonic acid, as a solid acid catalyst that was first introduced by Kiasat *et al.*, and silica boron sulfonic acid have many advantages such as simplicity in preparation, availability of precursor, economically benign, non-toxicity, and high activity/selectivity with excellent yields in various chemical processes.<sup>15</sup>

Synthesis of hybrid heterocycles that contain biologically active skeletons is an interesting subject in organic synthesis.<sup>16,17</sup> The

chromene ring system is used regularly as a scaffold in medicinal and agricultural chemistry.<sup>18,19</sup> Pyrano coumarins as a fused dihydropyran with a chromene nucleus received great attention due to their wide range of applications in various fields of chemistry.<sup>20,21</sup> They have exhibited various pharmacological activities such as anti-HIV, antitumor, anticancer, antibacterial, and anti-inflammatory properties.<sup>22,23</sup> Moreover, they can also be employed as cosmetics and pigments and utilized as potential biodegradable agrochemicals.<sup>24,25</sup> The unique properties and broad applications of pyrano coumarins have promoted extensive studies for the synthesis of these useful compounds.

Because one-pot multi-component reactions (MCRs) play an important role in combinatorial chemistry, this field remained one of the most interesting areas of research in recent years. During multi-component reactions, target compounds are formed by joining at least three functional groups through covalent bonds.<sup>26</sup> These reactions represent a very useful tool for the synthesis of complex molecules with potential biological properties because of their effective atom economy, convergent nature, and brief and straightforward experimental procedures.<sup>27</sup>

Herein, in continuation of our studies in the field of heterogeneous catalysts<sup>28–31</sup> and according to importance of pyrano coumarins, we wish to disclose, for the first time, the preparation and characterization of novel immobilized boron sulfonic acid onto Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub> nanoparticles (Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub>-BSA) as well as the examination of their catalytic application in the synthesis of pyrano coumarin derivatives.

## Experimental

All chemicals used in this research were purchased from Fluka and Merck chemical companies. The obtained products were identified by comparison of their spectral data and physical properties with previously reported data. The monitoring of the

Department of Chemistry, Yasouj University, Yasouj, Iran, 75918-74831. E-mail: farahimb@yu.ac.ir; Fax: +98-7412242167

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reaction progress and determination of purity of the compounds were accomplished using TLC performed with silica gel SIL G/UV254 plates. Melting points were determined by an electrothermal KSB1N apparatus and are uncorrected. The NMR spectra of  $^1\text{H}$  in DMSO were recorded on a Bruker Avance Ultra Shield 400 MHz spectrometer, and  $^{13}\text{C}$  NMR spectra were recorded at 100 MHz using TMS as an internal standard. Infrared (IR) spectra were obtained with a JASCO Fourier transform-infrared (FT-IR)/680 spectrometer using KBr pellets. X-ray powder diffraction (XRD) patterns were recorded using a Bruker AXS (D8 Advance) X-ray diffractometer with  $\text{Cu K}\alpha$  radiation ( $\lambda = 0.15418$  nm). The measurement was made in  $2\theta$  ranging from  $10^\circ$  to  $80^\circ$  at the speed of  $0.05^\circ \text{ min}^{-1}$ . Energy dispersive spectroscopy (EDS) was performed using a TESCAN Vega model instrument. The morphology of the particles was observed by scanning electron microscopy (SEM) under an acceleration voltage of 26 kV. The magnetic measurement was carried out in a vibrating sample magnetometer (VSM; Kashan University, Kashan, Iran) at room temperature.

### Preparation of $\text{Fe}_3\text{O}_4$

To synthesize  $\text{Fe}_3\text{O}_4$  magnetic nanoparticles through a chemical coprecipitation method, a solution of  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$  (2.7 g, 10 mmol) and  $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$  (1 g, 5 mmol) in 45 mL double distilled water was mechanically stirred under an argon atmosphere at  $80^\circ\text{C}$  for 30 min. In the next step, a sodium hydroxide solution (5 mL, 10 M) was gradually added dropwise. After continuous stirring at  $80^\circ\text{C}$  for 1 h under an argon atmosphere, the black precipitate of  $\text{Fe}_3\text{O}_4$  magnetic nanoparticles was decanted using an external magnetic field. The product was washed with double distilled water until pH 9 was obtained and then dried at  $60^\circ\text{C}$  under a vacuum.<sup>32</sup>

### Procedure for the synthesis of $\text{Fe}_3\text{O}_4$ -silica-coated nanoparticles

According to the current method in the literature, a suspension containing  $\text{Fe}_3\text{O}_4$  magnetic nanoparticles (1 g) was sufficiently dispersed in a mixture of ethanol (80 mL), distilled water (20 mL), concentrated ammonia aqueous solution (3 mL, 28%), and tetraethyl orthosilicate (0.5 mL). The reaction mixture was heated under reflux for 12 h. The  $\text{Fe}_3\text{O}_4$ -silica-coated ( $\text{Fe}_3\text{O}_4$ @- $\text{SiO}_2$ ) was separated by a magnet, washed several times with ethanol, and dried at  $60^\circ\text{C}$  in air.<sup>33</sup>

### Procedure for $\text{Fe}_3\text{O}_4$ @ $\text{SiO}_2$ -OB(OH) $_2$

A saturated solution of boric acid was added to a slurry containing  $\text{Fe}_3\text{O}_4$ @ $\text{SiO}_2$  nanoparticles (8 g) in dry toluene (45 mL). The mixture was refluxed for 24 h. The resultant suspension was collected using an external magnet and washed several times with distilled water and then methanol. It was dried at  $80^\circ\text{C}$  to obtain the brown solid named nano  $\text{Fe}_3\text{O}_4$ @ $\text{SiO}_2$ -OB(OH) $_2$ .<sup>34</sup>

### Procedure for the preparation of $\text{Fe}_3\text{O}_4$ @ $\text{SiO}_2$ -OB(OSO $_3\text{H}$ ) $_2$

In the final stage, a 100 mL suction flask was equipped with a dropping funnel containing chlorosulfonic acid (7.64 g, 0.066

mol), dry chloroform (40 mL), one argon inlet, and a gas outlet tube for conducting HCl gas over an adsorbing solution (10% NaOH). Then,  $\text{Fe}_3\text{O}_4$ @ $\text{SiO}_2$ -OB(OH) $_2$  (7.5 g) was charged into the flask. Chlorosulfonic acid was added drop-wise over a period of 60 min at  $0^\circ\text{C}$ . HCl gas immediately evolved from the reaction vessel. When the addition was completed, the mixture was sonicated for 1 h. The functionalized magnetic nanoparticles were collected by a magnet. The supernatant was decanted, and the nanoparticles were washed with dry chloroform ( $3 \times 5$  mL) and then dried in high vacuum overnight.

### General procedure for the synthesis of pyrano coumarins 4 and 6

$\text{Fe}_3\text{O}_4$ @ $\text{SiO}_2$ -BSA (0.005 g) was added to a mixture of malononitrile/ethyl cyanoacetate, aryl aldehyde, and 5,7-dihydroxy-4-substituted coumarin/4-hydroxycoumarin at  $80^\circ\text{C}$  under solvent-free conditions. The reaction progress was monitored by TLC (*n*-hexane/EtOAc, 3 : 2). After completion of the reaction, boiling EtOAc (10 mL) was added, and the catalyst was separated by filtration. To further purify the product, the obtained powder was recrystallized from EtOH.

**Compound 4e.** FT-IR (KBr):  $\nu_{\text{max}}$  3477, 3423, 3315, 1702, 1681  $\text{cm}^{-1}$ .  $^1\text{H}$  NMR (DMSO- $d_6$ , 400 MHz)  $\delta = 10.88$  (s, 1H), 7.61 (s, 2H), 7.25–7.05 (m, 5H), 6.39 (s, 1H), 6.04 (s, 1H), 3.50 (s, 2H), 3.44 (s, 1H), 2.66 (s, 3H), 1.02–1.11 (m, 3H) ppm.  $^{13}\text{C}$  NMR (DMSO- $d_6$ , 100 MHz)  $\delta = 168.47, 168.18, 159.97, 159.92, 159.45, 158.12, 158.12, 158.05, 154.23, 153.41, 147.54, 143.85, 143.69, 132.54, 131.78, 111.30, 110.01, 101.57, 98.09, 56.06, 24.11, 18.56, 14.27$  ppm. Anal. calcd for  $\text{C}_{22}\text{H}_{18}\text{ClNO}_6$ : C, 61.76; H, 4.24; N, 3.27. Found: C, 61.70; H, 4.26; N, 3.31. MS (*m/z*): 427  $[\text{M}]^+$ .

**Compound 4h.** FT-IR (KBr):  $\nu_{\text{max}}$  3413, 3311, 1687, 1625  $\text{cm}^{-1}$ .  $^1\text{H}$  NMR (DMSO- $d_6$ , 400 MHz)  $\delta = 10.81$  (s, 1H), 7.58 (s, 2H), 7.22–7.84 (m, 7H), 6.36 (s, 1H), 6.11 (s, 1H), 5.87 (s, 1H), 2.74 (m, 5H), 1.06 (t,  $J = 5.22$  Hz, 3H) ppm.  $^{13}\text{C}$  NMR (DMSO- $d_6$ , 100 MHz)  $\delta = 168.41, 160.07, 160.02, 159.44, 157.86, 153.89, 153.39, 147.61, 144.95, 132.86, 130.67, 127.87, 126.31, 126.23, 125.61, 125.16, 125.08, 124.93, 112.66, 111.32, 101.88, 98.08, 78.46, 50.23, 24.04, 18.52$  ppm. Anal. calcd for  $\text{C}_{26}\text{H}_{21}\text{NO}_6$ : C, 70.42; H, 4.77; N, 3.16. Found: C, 70.38; H, 4.80; N, 3.21.

**Compound 4r.** FT-IR (KBr):  $\nu_{\text{max}}$  3402, 1728, 1663  $\text{cm}^{-1}$ .  $^1\text{H}$  NMR (DMSO- $d_6$ , 400 MHz)  $\delta = 11.10$  (s, 1H), 8.18 (d,  $J = 8.8$  Hz, 2H), 7.44 (d,  $J = 8.4$  Hz, 2H), 7.17 (s, 2H), 6.51 (s, 1H), 6.12 (s, 1H), 4.82 (s, 1H), 2.63 (s, 3H) ppm.  $^{13}\text{C}$  NMR (DMSO- $d_6$ , 100 MHz)  $\delta = 160.02, 159.76, 157.97, 155.17, 153.76, 153.10, 147.99, 146.72, 128.92, 124.29, 120.17, 112.12, 107.55, 102.46, 99.11, 56.64, 36.81, 24.49$  ppm.

**Compound 6c.** FT-IR (KBr):  $\nu_{\text{max}}$  3380, 3311, 3189, 1714, 1675  $\text{cm}^{-1}$ .  $^1\text{H}$  NMR (DMSO- $d_6$ , 400 MHz)  $\delta = 7.92$  (d,  $J = 8$  Hz, 1H), 7.82 (s, 1H), 7.80 (d,  $J = 1.6$  Hz, 1H), 7.76 (d,  $J = 1.6$  Hz, 1H), 7.74 (s, 1H), 7.72 (d,  $J = 1.6$  Hz, 1H), 7.54 (s, 1H), 7.52 (s, 1H), 7.49 (t,  $J = 3.6$  Hz, 2H), 7.47 (s, 1H) ppm.  $^{13}\text{C}$  NMR (DMSO- $d_6$ , 100 MHz)  $\delta = 160.0, 158.5, 154.4, 152.7, 149.2, 133.5, 132.9, 129.3, 125.1, 123.0, 119.4, 119.2, 117.0, 113.4, 110.4, 103.3, 57.3, 37.5$  ppm. Anal. calcd for  $\text{C}_{20}\text{H}_{11}\text{N}_3\text{O}_3$ : C, 70.38; H, 3.25; N, 12.31. Found: C, 70.42; H, 3.20; N, 12.25.



**Compound 6e.** FT-IR (KBr):  $\nu_{\max}$  3391, 3180, 1712, 1674, 1608  $\text{cm}^{-1}$ .  $^1\text{H}$  NMR (DMSO- $d_6$ , 400 MHz)  $\delta$  = 7.90 (dd,  $J$  = 8.0 Hz, 1H), 7.73–7.69 (m, 1H), 7.44–7.38 (m, 7H), 7.18 (d,  $J$  = 8.8 Hz, 2H), 6.95 (d,  $J$  = 8.8 Hz, 2H), 5.06 (s, 2H), 4.40 (s, 1H) ppm.  $^{13}\text{C}$  NMR (DMSO- $d_6$ , 100 MHz)  $\delta$  = 159.51, 157.87, 157.45, 153.09, 152.06, 137.05, 135.60, 132.83, 128.76, 128.40, 127.79, 127.64, 124.63, 122.41, 119.30, 116.53, 114.61, 112.97, 104.19, 69.17, 58.09, 36.13 ppm.

**Compound 6i.** FT-IR (KBr):  $\nu_{\max}$  3461, 3295, 3162, 1716, 1673, 1631  $\text{cm}^{-1}$ .  $^1\text{H}$  NMR (DMSO- $d_6$ , 400 MHz)  $\delta$  = 8.86 (s, 1H), 7.90 (d,  $J$  = 8 Hz, 1H), 7.74 (t,  $J$  = 8 Hz, 2H), 7.46–7.52 (m, 2H), 7.34 (s, 1H), 6.81 (d,  $J$  = 2 Hz, 1H), 6.72 (d,  $J$  = 2.1 Hz, 1H), 6.64 (d,  $J$  = 8.4 Hz, 1H), 4.35 (s, 1H), 3.94–4.01 (m, 2H), 1.32 (t,  $J$  = 6.8 Hz, 3H) ppm.  $^{13}\text{C}$  NMR (DMSO- $d_6$ , 100 MHz)  $\delta$  = 160.0, 158.3, 153.4, 152.5, 146.5, 134.7, 133.2, 15.0, 122.9, 120.3, 119.8, 117.0, 116.0, 114.0, 113.5, 104.8, 64.4, 58.8, 36.9, 15.1 ppm. Anal. calcd for  $\text{C}_{21}\text{H}_{16}\text{N}_2\text{O}_5$ : C, 67.02; H, 4.28; N, 7.44. Found: C, 67.12; H, 4.20; N, 7.51.

## Results and discussion

The new magnetic nano-catalyst  $\text{Fe}_3\text{O}_4@(\text{SiO}_2\text{-BSA})$  was prepared following the protocol shown in Scheme 1. Firstly, in order to prepare the magnetic  $\text{Fe}_3\text{O}_4$  nanoparticles, the chemical coprecipitation of  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  ions in NaOH solution was performed.<sup>32</sup> Subsequently, the silica-coated magnetic nanoparticles ( $\text{Fe}_3\text{O}_4@(\text{SiO}_2)$ ) were easily achieved with the known Stober method.<sup>32</sup> Then,  $\text{Fe}_3\text{O}_4@(\text{SiO}_2\text{-OB}(\text{OH})_2)$  was synthesized from the reaction of  $\text{Fe}_3\text{O}_4@(\text{SiO}_2)$  with boric acid in dry toluene under reflux.<sup>34</sup> Finally, the surface of  $\text{Fe}_3\text{O}_4@(\text{SiO}_2\text{-OB}(\text{OH})_2)$  was functionalized with chlorosulfonic acid to obtain  $\text{Fe}_3\text{O}_4@(\text{SiO}_2\text{-OB}(\text{OSO}_3\text{H})_2)$ . Chemical analysis of prepared  $\text{Fe}_3\text{O}_4@(\text{SiO}_2\text{-OB}(\text{OSO}_3\text{H})_2)$  was performed using FT-IR, EDX, XRD, and SEM; magnetic measurements were performed using VSM.

The FT-IR spectra of  $\text{Fe}_3\text{O}_4$ ,  $\text{Fe}_3\text{O}_4@(\text{SiO}_2)$ ,  $\text{Fe}_3\text{O}_4@(\text{SiO}_2\text{-OB}(\text{OH})_2)$ , and  $\text{Fe}_3\text{O}_4@(\text{SiO}_2\text{-BSA})$  were compared with each other (Fig. 1). The appearance of peaks around 570  $\text{cm}^{-1}$ , 796  $\text{cm}^{-1}$ , 1097  $\text{cm}^{-1}$ , 478  $\text{cm}^{-1}$ , and 3413  $\text{cm}^{-1}$  in all of these four spectra are relevant to Fe–O stretching, Si–O–Si symmetric and asymmetric stretching, bending vibration, and OH vibration,

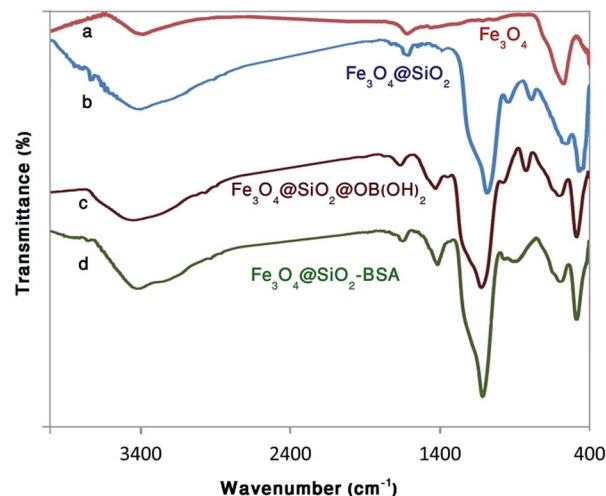


Fig. 1 The FT-IR of (a)  $\text{Fe}_3\text{O}_4$ , (b)  $\text{Fe}_3\text{O}_4@(\text{SiO}_2)$ , (c)  $\text{Fe}_3\text{O}_4@(\text{SiO}_2@(\text{OB}(\text{OH})_2))$ , and (d)  $\text{Fe}_3\text{O}_4@(\text{SiO}_2\text{-BSA})$ .

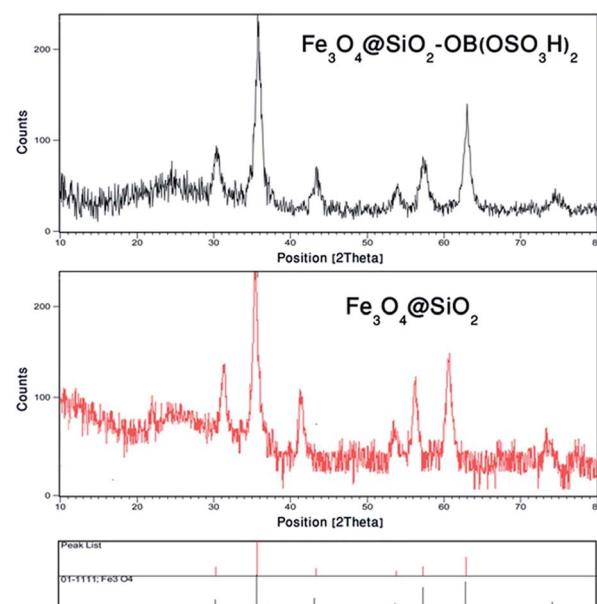
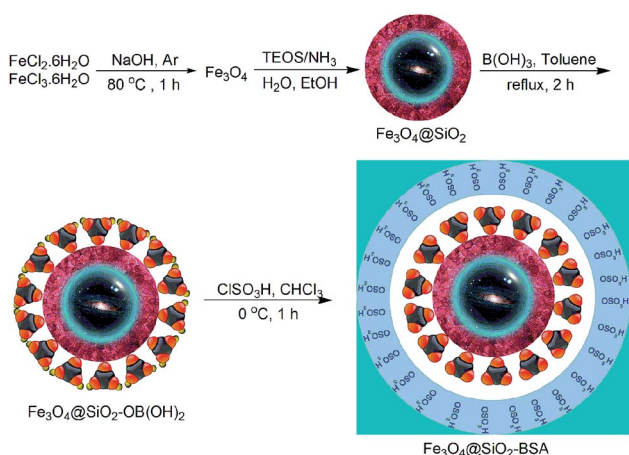


Fig. 2 XRD patterns of  $\text{Fe}_3\text{O}_4$ ,  $\text{Fe}_3\text{O}_4@(\text{SiO}_2)$ , and  $\text{Fe}_3\text{O}_4@(\text{SiO}_2\text{-BSA})$ .



Scheme 1 Synthesis of  $\text{Fe}_3\text{O}_4@(\text{SiO}_2\text{-BSA})$ .

respectively, which was confirmed to preserve the nano-structure of  $\text{Fe}_3\text{O}_4$  and  $\text{Fe}_3\text{O}_4@(\text{SiO}_2)$ .<sup>35</sup> The peak in the region of approximately 1400  $\text{cm}^{-1}$  of spectra c and d can be related to B–O.<sup>36</sup> The O=S=O asymmetric and symmetric stretching vibrations near 1200–1250  $\text{cm}^{-1}$  and 1010–1100  $\text{cm}^{-1}$ , and the S–O stretching vibration of  $-\text{SO}_3\text{H}$  at 650  $\text{cm}^{-1}$  and 3180 to 3419  $\text{cm}^{-1}$  were seen in d spectra for the sulfonic group of the catalytic surface.<sup>37</sup>

To investigate the quantity of crystalline phases of the new catalyst, its XRD-diffraction pattern was obtained, as shown in Fig. 2. The control of six characteristic peaks at 30.3909, 35.7981, 43.4418, 53.9044, 57.4051, and 63.0226 that correspond to the (2 2 0), (3 1 1), (4 0 0), (4 2 2), (5 1 1), and (4 4 0) crystal planes is very important because the preservation of the cubic spinel structure could be strictly confirmed (JCPD 00-001-1111 standard). Additionally, there was a broad peak from  $2\theta = 19$  to 28 that



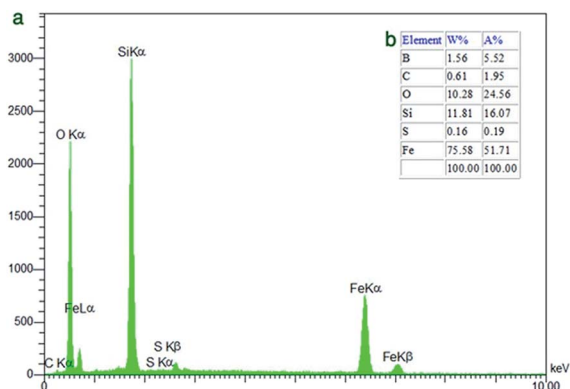


Fig. 3 (a) Energy-dispersive X-ray spectroscopy (EDS) spectra of  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$ . (b) EDS data for  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$ .

was due to the  $\text{SiO}_2$  shells of the coated  $\text{Fe}_3\text{O}_4$ .<sup>38</sup> The other existing groups in the catalyst did not exhibit any changes in the crystal structure. The particle size of the prepared catalyst can be calculated using the Debye–Scherrer equation:

$$D = 0.94\lambda/\beta \cos \theta$$

where  $D$  is the average particle diameter, 0.94 is the Scherrer's constant,  $\lambda$  is the X-ray wavelength (1.5406 Å for Cu Kα),  $\beta$  is the half width of XRD diffraction lines, and  $\theta$  is the Bragg's angle in degrees. The particle size relevant to the Debye–Scherrer equation is calculated as 88.8 nm.

Energy-dispersive X-ray spectroscopy (EDS) is one of the best approaches to determine catalyst purity. Fig. 3 shows the EDS spectra indicating the elemental composition of the catalyst. It contains no impurity elements other than Fe, O, Si, S, and B. It must be noted that failure of the boron peak is observed because of the overlap between peaks of boron and other elements.<sup>36</sup>

The SEM image of  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$  in Fig. 4 shows that the average diameter range was 58–86 nm, indicating good harmony in comparison with the calculated result from the Debye–Scherrer equation. Also, the uniform core–shell morphology was consistent

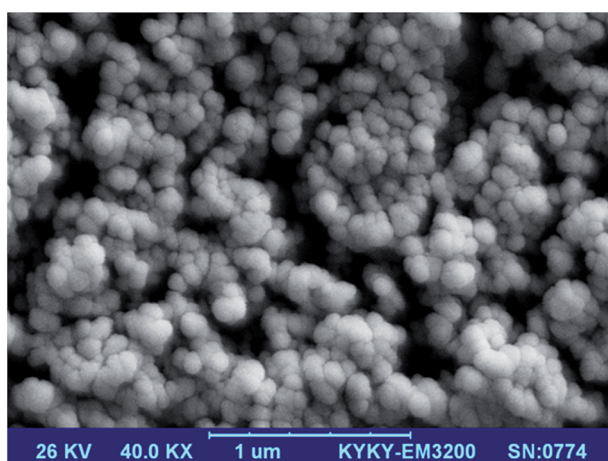


Fig. 4 SEM image of the catalyst.

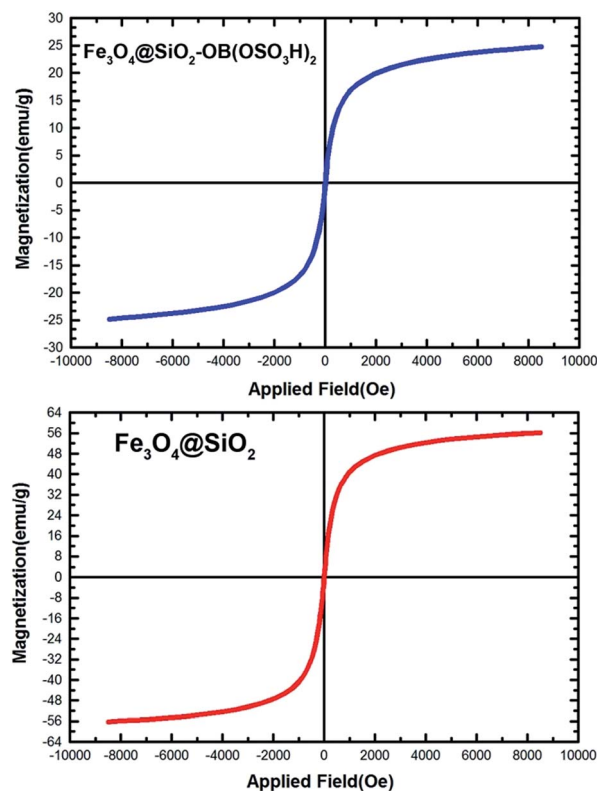


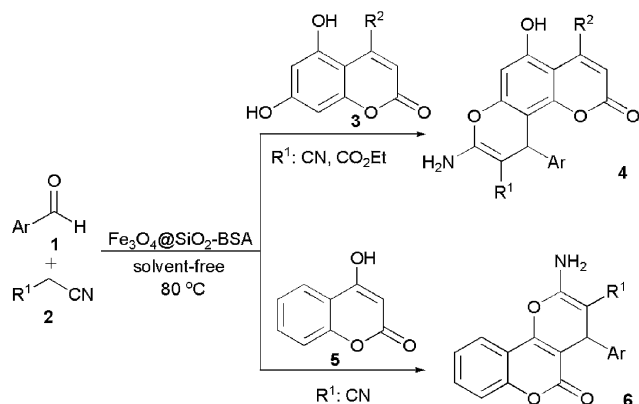
Fig. 5 The vibrating sample magnetometer (VSM) magnetization curves of  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$  in comparison with  $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ .

with the spherical shape of the  $\text{Fe}_3\text{O}_4$  nanoparticles. We commonly used a vibrating sample magnetometer to evaluate the magnetic measurement of our catalyst. Fig. 5 shows the magnetic behavior at room temperature for the catalyst. The below magnetization curves indicate the saturation magnetization of  $\text{Fe}_3\text{O}_4@/\text{SiO}_2$  nanoparticles and  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$ , which were diminished to  $24.8 \text{ emu g}^{-1}$  from  $56.2 \text{ emu g}^{-1}$  for  $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ .

To show the catalytic activity of  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$ , it was used as a catalyst in the synthesis of a range of known and novel pyrano coumarins **4** and **6** *via* the three-component reactions of aryl aldehydes **1**, active methylene compound **2** (malononitrile or ethyl cyanoacetate), and hydroxycoumarin (5,7-dihydroxy-4-substituted coumarins **3** or 4-hydroxycoumarin **5**) under solvent-free conditions (Scheme 2).

To initiate the synthetic work, several 5,7-dihydroxy-4-substituted coumarins **3** were prepared in good yields according to previously published methods.<sup>39</sup> Subsequently, in order to find the most appropriate reaction conditions, a three-component reaction of ethyl cyanoacetate, benzaldehyde, and 4-methyl-5,7-dihydroxycoumarin was screened as a model reaction. The desired product was not produced in the absence of a catalyst even after a long reaction time. Therefore, the model reaction was performed using  $\text{Fe}_3\text{O}_4@/\text{SiO}_2@(\text{CH}_2)_3\text{-OMoO}_3\text{H}$  at various conditions. On the basis of the results obtained, we found that this reaction was efficiently performed in the presence of 0.005 g of  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$  at  $80^\circ\text{C}$  under solvent-free conditions (Table 1).





Scheme 2 Preparation of pyrano coumarins **4** and **6** in the presence of  $\text{Fe}_3\text{O}_4@SiO_2\text{-BSA}$  as catalyst.

Table 1 Screening conditions for the model reaction

Entry	Catalyst (g)	Solvent	<i>T</i> (°C)	Yield <sup>a</sup> (%)
1	0.001	None	70	30
2	0.002	None	70	40
3	0.003	None	70	45
4	0.004	None	70	47
5	0.005	None	70	70
6	0.006	None	50	70
7	0.005	None	60	60
8	0.005	None	80	90
9	0.005	None	90	90
10	0.005	None	100	90
11	0.005	MeOH	Reflux	65
12	0.005	EtOH	Reflux	67
13	0.005	EtOH/H <sub>2</sub> O	Reflux	55
14	0.005	CH <sub>3</sub> CN	Reflux	73
16	0.005	Toluene	Reflux	60

<sup>a</sup> Isolated yields.

With optimal conditions established, we then examined the scope of the reaction for the construction of various substrates including malononitrile, various aromatic aldehydes, and diverse 5,7-dihydroxy-4-substituted coumarin derivatives; the results are summarized in Table 2. In general, the reaction proceeded smoothly to afford the desired products **4** in good to excellent yields.

Encouraged by these results, we extended the catalytic activity of  $\text{Fe}_3\text{O}_4@SiO_2\text{-BSA}$  to condensation reactions of aromatic aldehydes, malononitrile, and 4-hydroxycoumarin to afford pyrano coumarins **6** (Scheme 2). A series of product **6** with different substituents was prepared from different aromatic aldehydes bearing electron-withdrawing and electron-donating groups (Table 3).

The structures of the obtained products **4** and **6** were deduced from their elemental analysis, IR, <sup>1</sup>H, and <sup>13</sup>C NMR spectroscopy and they were compared with authentic samples.<sup>40–42</sup> Although both electron-rich and electron-poor aldehydes afforded the desired products **4** and **6**, aldehydes having electron-withdrawing groups in comparison with those having electron-donating ones

Table 2  $\text{Fe}_3\text{O}_4@SiO_2\text{-BSA}$ -catalyzed synthesis of pyrano coumarins **4**

Entry	Ar	<i>R</i> <sup>1</sup>	<i>R</i> <sup>2</sup>	Mp (°C)	Yield <sup>a</sup> (%)
<b>4a</b>	C <sub>6</sub> H <sub>5</sub>	CO <sub>2</sub> Et	CH <sub>3</sub>	260–262	90
<b>4b</b>	4-CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub>	CO <sub>2</sub> Et	CH <sub>3</sub>	280–282	75
<b>4c</b>	4-BrC <sub>6</sub> H <sub>4</sub>	CO <sub>2</sub> Et	CH <sub>3</sub>	215–217	86
<b>4d</b>	3-BrC <sub>6</sub> H <sub>4</sub>	CO <sub>2</sub> Et	CH <sub>3</sub>	271–273	90
<b>4e</b>	2-ClC <sub>6</sub> H <sub>4</sub>	CO <sub>2</sub> Et	CH <sub>3</sub>	274–276	93
<b>4f</b>	2,4-Cl <sub>2</sub> C <sub>6</sub> H <sub>3</sub>	CO <sub>2</sub> Et	CH <sub>3</sub>	251–253	89
<b>4g</b>	2-Cl-6-FC <sub>6</sub> H <sub>3</sub>	CO <sub>2</sub> Et	CH <sub>3</sub>	234–235	87
<b>4h</b>	1-Naphthyl	CO <sub>2</sub> Et	CH <sub>3</sub>	208–210	75
<b>4i</b>	C <sub>6</sub> H <sub>5</sub>	CN	CH <sub>3</sub>	250–251	85
<b>4j</b>	4-ClC <sub>6</sub> H <sub>4</sub>	CN	CH <sub>3</sub>	245–247	93
<b>4k</b>	3-ClC <sub>6</sub> H <sub>4</sub>	CN	CH <sub>3</sub>	202–204	96
<b>4l</b>	2-ClC <sub>6</sub> H <sub>4</sub>	CN	CH <sub>3</sub>	325–326	90
<b>4m</b>	2,4-Cl <sub>2</sub> C <sub>6</sub> H <sub>3</sub>	CN	CH <sub>3</sub>	320–321	85
<b>4n</b>	4-CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub>	CN	CH <sub>3</sub>	221–222	70
<b>4o</b>	4-OCH <sub>3</sub> C <sub>6</sub> H <sub>4</sub>	CN	CH <sub>3</sub>	260–262	65
<b>4p</b>	2-OCH <sub>3</sub> C <sub>6</sub> H <sub>4</sub>	CN	CH <sub>3</sub>	300–301	70
<b>4q</b>	3-BrC <sub>6</sub> H <sub>4</sub>	CN	CH <sub>3</sub>	296–298	90
<b>4r</b>	4-NO <sub>2</sub> C <sub>6</sub> H <sub>4</sub>	CN	CH <sub>3</sub>	341–342	85
<b>4s</b>	3-NO <sub>2</sub> C <sub>6</sub> H <sub>4</sub>	CN	CH <sub>3</sub>	390–391	87
<b>4t</b>	2-ClC <sub>6</sub> H <sub>4</sub>	CN	Ph	241–242	85
<b>4u</b>	2-ClC <sub>6</sub> H <sub>4</sub>	CN	CH <sub>2</sub> Cl	305–306	91

<sup>a</sup> Isolated yield.

performed this transformation in better yields. This may be explained according to more positive charges located on the carbonyl group of aldehydes in electron-poor cases, which makes it a more reactive electrophile center.

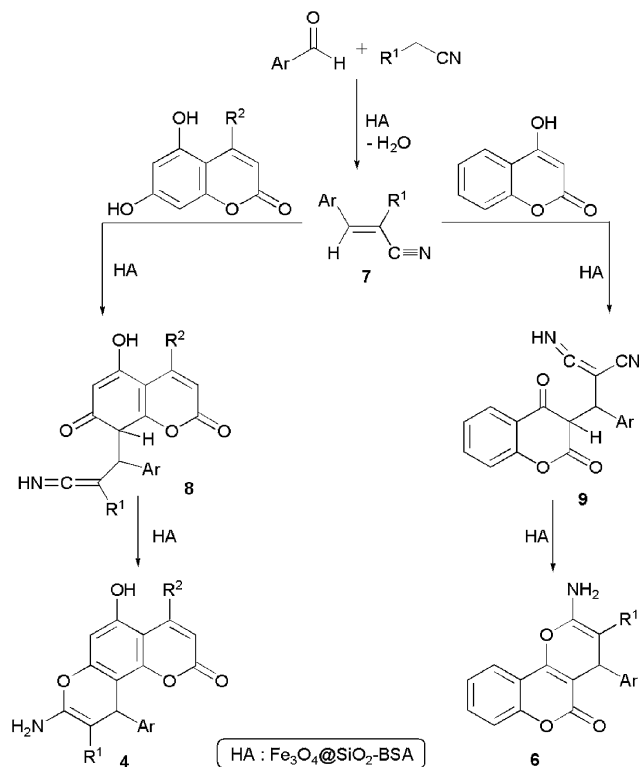
A plausible mechanism for the synthesis of pyrano coumarins is outlined in Scheme 3. Initially, intermediate **7** is formed *via* the Knoevenagel condensation of the aldehyde and active methylene compound. For the formation of pyrano coumarin **4**, adduct **8** results from a Michael-type addition of C-8 of dihydroxycoumarin to compound **7**. Subsequently, cyclization of intermediate **8** gives pyrano coumarin **4**. 4-Hydroxycoumarin can also attack

Table 3 Synthesis of pyrano coumarins **6** using  $\text{Fe}_3\text{O}_4@SiO_2\text{-BSA}$

Entry	Ar	Mp (°C)	Yield <sup>a</sup> (%)
<b>6a</b>	C <sub>6</sub> H <sub>5</sub>	261–263	85
<b>6b</b>	4-CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub>	255–257	90
<b>6c</b>	4-CNC <sub>6</sub> H <sub>4</sub>	252–254	83
<b>6d</b>	4-Iso-propylC <sub>6</sub> H <sub>4</sub>	240–242	87
<b>6e</b>	4-BenzoyloxyC <sub>6</sub> H <sub>4</sub>	268–269	78
<b>6f</b>	3-BrC <sub>6</sub> H <sub>4</sub>	276–277	95
<b>6g</b>	2-Cl-6-FC <sub>6</sub> H <sub>3</sub>	293–295	80
<b>6h</b>	1-Naphthyl	260–261	86
<b>6i</b>	3-OEt-4-OHC <sub>6</sub> H <sub>3</sub>	244–245	75
<b>6j</b>	Thiophene-2-yl	265–266	80
<b>6k</b>	4-OCH <sub>3</sub> C <sub>6</sub> H <sub>4</sub>	246–248	85
<b>6l</b>	4-NO <sub>2</sub> C <sub>6</sub> H <sub>4</sub>	260–262	90
<b>6m</b>	4-ClC <sub>6</sub> H <sub>4</sub>	262–264	87
<b>6n</b>	3-NO <sub>2</sub> C <sub>6</sub> H <sub>4</sub>	263–265	80
<b>6o</b>	2-ClC <sub>6</sub> H <sub>4</sub>	269–271	83
<b>6p</b>	2,4-Cl <sub>2</sub> C <sub>6</sub> H <sub>3</sub>	259–260	80

<sup>a</sup> Isolated yield.





Scheme 3 Proposed mechanism for the synthesis of 4 and 6 in the presence of  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$ .

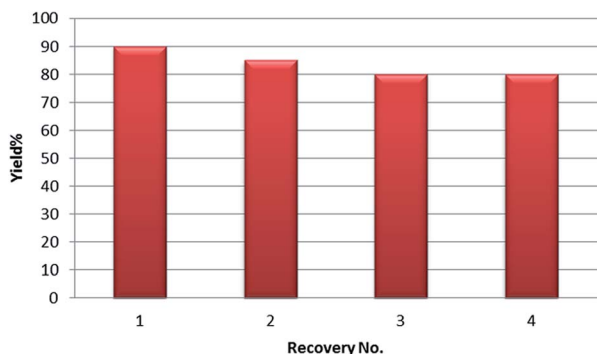


Fig. 6 Reusability study of  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$  in the synthesis of 4a at  $80^\circ\text{C}$  under solvent-free conditions.

intermediate 7 to produce 9, which is then converted to pyrano coumarin 6 after an intramolecular cyclization.

The recovery and reusability of catalyst are quite preferable because they are eco-friendly procedures. The recovered  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$  from the model reaction for the synthesis of 4a was regenerated by washing with chloroform and drying at  $120^\circ\text{C}$  for 1 hour. Using the recycled catalyst four consecutive times in the model reaction gave the product with a gradually decreasing reaction yield (Fig. 6).

## Conclusions

In summary, for the first time, a new modified magnetic nanoparticle-bearing boron sulfonic acid,  $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-BSA}$ ,

was prepared, characterized, and applied as a heterogeneous and efficient acid catalyst for the synthesis of a series of functionalized heterocyclic compounds containing the coumarin moiety *via* a one-pot three-component reaction. Our work presents a very simple reaction performed in the absence of hazardous organic solvents. Reusability of the catalyst, operational simplicity, and good chemical yields, combined with step- and atom-economic aspects, make this strategy highly attractive. It is worthwhile to note that the products are potentially valuable for further synthetic manipulation because of the presence of transformable functionalities.

## Conflicts of interest

There are no conflicts to declare.

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