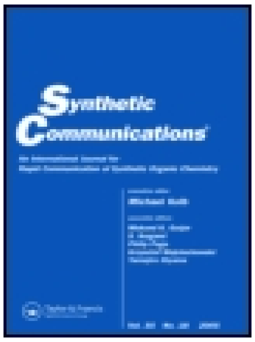

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Sulfonic acid-functionalized magnetic $Fe_{3-x}Ti_xO_4$ nanoparticles: new recyclable heterogeneous catalyst for one-pot synthesis of tetrahydrobenzo[b]pyrans and dihydropyrano[2,3-c]pyrazole derivatives

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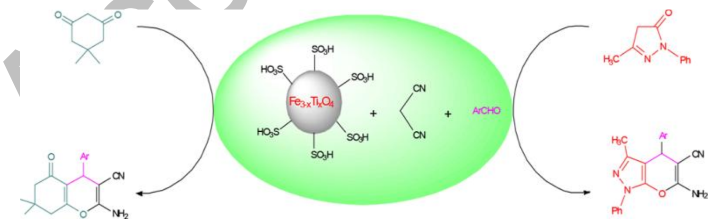
Abstract

In this work, titanomagnetite nanoparticles ($Fe_{3-x}Ti_xO_4$) have been used as novel suppport for the synthesis of a magnetic acidic catalyst. These nanoparticles were functionalized with sulfonic acid groups in order to prepare the $Fe_{3-x}Ti_xO_4@SO_3H$ nanoparticles. The synthesized acidic nanoparticles have been explored as new and efficient recyclable heterogeneous catalyst for one-pot three-component synthesis of tetrahydrobenzo[b]pyrans known as 4*H*-chromenes and 1,4-dihydropyrano[2,3-c]pyrazoles. The structure of the catalyst was established by FT-IR, EDX and SEM analyses. The reactions proceed smoothly to furnish the respective products in excellent yields and low reaction times. The facile reaction conditions, easy isolation of the products, versatility and easy magnetic separation and reusability of the catalyst with no significant loss of activity are the main merits of the present method.



KEYWORDS: Magnetic catalyst, Chromene, Nanocatalyst, Pyranopyrazole, Titanomagnetite

INTRODUCTION

In the last few decades, the heterogeneous catalysts have found world-wide applications as eco-friendly and economically viable catalysts in organic transformations.[1] Many of these catalysts have attracted enormous research interests academically and in industrial fields of catalysts.[1] Among the heterogeneous catalysts, various nanoparticles (NPs) as catalysts have received considerable attention owing to their high catalytic performance and selectivity in various fields of synthetic organic and bioorganic chemistry.[2–6] Recently, several economical and environmentally friendly approaches have been developed for the preparation of nano-catalysts in order to replace the unstable, non-selective, or toxic catalysts.[7,8] An important group of nano-catalysts belong to nanometal oxides of various structures which have found wide applications in different research and technological areas.[9,10] A number of nanometal oxides, in particular Fe_3O_4, TiO_2, Al_2O_3, ZnO, etc., exhibit extraordinary physical and chemical properties such as Lewis acid-base characters on their surfaces.[11–13] Moreover, nanometal oxides are excellent adsorbents and supports for a variety of organic catalysts with enhancing their reactivity in chemical transformations. Superiority of these nanometal oxides over many other heterogeneous catalysts stems from their strong oxidizing power, selectivity, non-toxicity, reusability, long-term stability, and high activity because of their high number of surface atoms.[14,15] In addition, the high ratio of surface area to volume of these nanometals is mainly responsible for their catalytic and supporting abilities.[16] To improve the catalytic activity and recyclability, considerable developments have been made on the synthesis and use of magnetic nanoparticles (MNPs), mainly on magnetic nanometal oxides.[17] Magnetic nanoparticles have been used widely as catalysts or supports in various industrial and biological fields such as magnetic resonance imaging (MRI), drug delivery, bioseparation, hyperthermia, and catalytic reactions.[12,13,17–26] Moreover, magnetic NPs are similarly used as excellent adsorbents and supports in conjunction with a wide variety of organic catalysts,[18–21,27–32] and molecules to enhance their reactivity in organic reactions. Such nanocatalysts can be easily separated from the reaction products simply by employing an external magnet and reused efficiently with no considerable loss of activity. The surface of magnetic metal oxide nanoparticles such as Fe_3O_4 NPs can be functionalized and modified by various organic and inorganic materials such as silica, polymers, biomolecules, metals, etc., which have been used as selective and efficient catalysts in a wide range of reactions.[33–39] Among the catalysts supported with magnetic nanometal oxides, various nano-oxide particles functionalized with different acidic groups such as phosphotungstic acid ($H_3PW_{12}O_{40}$), Preyssler-type heteropolyacid, sulfamic and sulfonic acids have been grafted on the surface of magnetic nanoparticles and successively used for selectively catalyzing chemical reactions.[39–41]

Tetrahydrobenzo[b]pyrans known as 4*H*-chromenes are well-documented heterocyclic compounds of vital biological and industrial importance.[42] These compounds perform vital pharmacological activities as anticoagulant, anticancer, spasmolytic, diuretic, and anti-anaphylactic agents.[43–45] Also, 4*H*-chromenes have been widely used as cosmetics, pigments, and potentially biodegradable agrochemicals.[46] Recently, an efficient method has been reported for the synthesis of 4*H*-chromenes using silica-bonded propylpiperazine-*N*-sulfamic acid as green heterogeneous catalyst under solvent-free conditions.[47] In addition, a novel magnetically immobilized organocatalyst fabricated by covalently anchoring 2-aminomethylphenol moiety on the surface of hydroxyapatite-encapsulated maghemite nanoparticles has been explored for the preparation of benzo[b]pyrans and dihydropyrano[c]chromenes.[48]

Similarly, 1,4-dihydropyrano[2,3-c]pyrazoles form another important class of heterocyclic compounds which constitute important precursors to promising drugs in the field of medicinal chemistry and exhibit wide range of biological activities such as antibacterial, anticoagulant, anticancer, diuretic and insecticidal properties.[49–51]

Following our ongoing efforts for the development of more benign and efficient nanocatalysts for the synthesis of various heterocyclic compounds and other organic transformations, in this work, we were prompted to initiate the hitherto unreported synthesis of sulfonic acid-functionalized titanomagnetite and examine its catalytic capability in one-pot three-component synthesis of 4*H*-chromenes (**2a-k**) and pyrano[2,3-c]pyrazoles (**3a-i**) (Scheme 1).

RESULTS AND DISCUSSION

Characterization Of The Catalyst $Fe_{3-X}ti_xo_4@SO_3H$ Mnps

In continuation of our efforts to develop clean and green recovery of the heterogeneous catalyst, herein, we are encouraged to synthesize the sulfonic acid-functionalized titanomagnetite ($Fe_{3-x}Ti_xO_4@SO_3H$) nanoparticles as a new nanomagnetic heterogeneous system. It is a known fact that, the presence of Ti^{+4} cations in the structure of nanoparticles can increase the number of superficial hydroxyl groups.[52] Such a structural quality can improve the loading capacity of sulfonic acid groups on the surface of the titanomagnetite nanoparticles (4.1-5.5 mmol/g) compared with the magnetite Fe_3O_4 NPs (1.76 mmol/g),[53] and magnetite silica-coated Fe_3O_4 NPs (0.32 mmol/g).[54]

Firstly, $Fe_{3-x}Ti_xO_4$ MNPs were prepared using the similar procedure as previously reported by Yang and co-workers,[55] by treatment of the mixture of equimolar amounts of $FeSO_4.7H_2O$ and $TiCl_4$ in acidic solution with hydrazine monohydrate in deionized water with refluxing under nitrogen atmosphere. The resulting titanomagnetite nanoparticles were separated from the reaction mixture simply by using a magnetic bar. Then, a dispersion of $Fe_{3-x}Ti_xO_4$ MNPs in CH_2Cl_2 was ultrasonicated for 30 min followed by treatment with chlorosulfonic acid with stirring at room temperature. The resulting $Fe_{3-x}Ti_xO_4@SO_3H$ MNPs were isolated by using a magnetic bar. The number of SO_3H groups per gram of the support NPs determined by acid-base titration was found to be in the range of 4.1-5.5 mmol.

The synthesized catalyst was characterized by different methods such as Fourier transform infrared (FT-IR) spectral, energy dispersive X-ray (EDX), and scanning electron microscopical (SEM) analyses.

The FT-IR spectra of $Fe_{3-x}Ti_xO_4$ and $Fe_{3-x}Ti_xO_4@SO_3H$ are shown in Fig. 1a and 1b respectively. The spectrum of the $Fe_{3-x}Ti_xO_4@SO_3H$ NPs consists of the peaks that are characteristic of SO_3H-functionalized nanoparticles which are clearly different from those of the unfunctionalized $Fe_{3-x}Ti_xO_4$ NPs (Fig. 1a), namely indicates the successful conjugation of sulfonic acid groups onto the surface of the $Fe_{3-x}Ti_xO_4$ MNPs. The broad absorption band centered at 3416 cm^{-1} in the IR spectrum of the $Fe_{3-x}Ti_xO_4$ (Fig. 1a) is assigned to the incorporation of symmetrical and asymmetrical modes of the O-H bonds which are attached to the surface metal atoms. The broad band appearing at 3000-3500 cm^{-1} along with the peaks at 1195 and 1132 cm^{-1} are attributed to the hydroxyl group of the sulfonic acid groups (Fig. 1b). The band for Ti-O bond is present at 735 cm^{-1}.[56,57] In both of these IR spectra, the broad sharp peaks appearing at 578 and 534 cm^{-1} respectively are ascribed to Fe-O stretching vibrations.

As shown in Fig. 2, the energy dispersive X-ray spectrum (EDX) obtained from the synthesized $Fe_{3-x}Ti_xO_4@SO_3H$ MNPs clearly indicates the expected elemental composition (O, S, Ti, Fe).

The morphology and particle size of the $Fe_{3-x}Ti_xO_4@SO_3H$ NPs were observed by scanning electron microscopical (SEM) analysis as shown in Fig. 3. From SEM image it can be seen that the $Fe_{3-x}Ti_xO_4@SO_3H$ NPs are spherical in shape and the average size of these MNPs is estimated to be in the range of 30-50 nm.

Catalytic Activity Of $Fe_{3-X}ti_xo_4@SO_3H$ Mnps For The Synthesis Of 4H-Chromenes And 1,4-Dihydropyrano[2,3-C]Pyrazoles

In order to evaluate the merit and the catalytic capability of the synthesized heterogeneous catalyst $Fe_{3-x}Ti_xO_4@SO_3H$ MNPs in organic reactions, we chose to examine its catalytic activity in one-pot three-component synthesis of tetrahydrobenzo[b]pyrans (4*H*-chromenes) and dihydropyrano[2,3-c]pyrazoles. Initially, we investigated the reaction between 4-chlorobenzaldehyde, malononitrile and 5,5-dimethyl-1,3-cyclohexanedione (dimedone) as simple model reaction. To establish the reaction conditions, the effects of different reaction parameters such as the catalyst loading, solvent and temperature were screened on the rate and yield of the model reaction. According to the experimental results as summarized in Table 1, the best results in terms of the reaction rates and yields were obtained when the reaction was carried out in the mixture of EtOH and H_2O in equal volumes as the solvent of choice, under reflux conditions with using 0.03 g catalyst loading (entry 8). In addition, the important role of the catalyst in the reaction was approved by repeating the reaction in the absence of the catalyst under optimized conditions and noting that only low yields of the expected product were formed (entries 12).

In a similar way, the synthesis of 1,4-dihydropyrano[2,3-c]pyrazoles from the one-pot three-component condensation reaction between 4-chlorobenzaldehyde, 3-methyl-1-phenyl-2-pyrazolin-5-one, and malononitrile as another model reaction was chosen to further examine the versatility and catalytic potential of the catalyst. To establish the reaction conditions, we studied the effects of the same green solvents H_2O and EtOH, catalyst loading and reaction temperature on the reaction. Based on the experimental results summarized in Table 2, the optimal results for the reaction are obtained under solvent-free condition with using a catalyst loading of 0.05 g at 105°C (entry 10). Further increasing the amount of the catalyst had no improving effect on the yield (entry 12). The vital involvement of the catalyst in the reaction was substantiated by conducting the reaction in the absence of the catalyst that resulted in no detectable amount of the expected product with almost full recovery of the starting materials (entry 13).

To develop the scope of the reactions, we conducted these reactions with a series of aldehydes under the optimized conditions, *i.e*. the catalyst loading of 0.03 g, mixed H_2O/EtOH under reflux condition for the synthesis of 4*H*-chromenes **2a-k,** and the catalyst loading of 0.05 g, solvent-free, and the reaction temperature 105°C for the synthesis of 1,4-dihydropyrano[2,3-c]pyrazoles **3a-i**. All the reactions proceeded smoothly to afford the products in high yields. The experimental results are summarized in Tables 3 and 4 respectively. As shown in these Tables, the aldehydes carrying electron-donating and electron-withdrawing groups all undergo these reactions to afford the corresponding products in excellent yields irrespective of the nature of the substituent groups.

All the products are known compounds which were characterized by their melting points and spectral (FT-IR, ^{1}H NMR) analysis and compared with those reported in the literature.

Proposed Catalytic Reaction Mechanisms

A possible mechanism to explain the one-pot three-component condensation reaction between aldehydes, malononitrile and dimedone is depicted in Scheme 2. As shown in this scheme, it is likely that, the initial step involves the condensation of the aldehyde with malononitrile under the activation of $Fe_{3-x}Ti_xO_4@SiO_3H$ followed by dehydration to produce the arylidenemalononitrile intermediate **I**. Subsequently, the catalyst-induced nucleophilic addition of the enolizable dimedone to the intermediate **I** followed by consecutive intramolecular cyclization occur to provide the intermediate **II** which rearranges to afford the expected 4*H*-chromene.

Also, a plausible reaction mechanism suggested for the synthesis of 1,4-dihydropyrano[2,3-c]pyrazoles in the presence of the same catalyst is illustrated in Scheme 3. Similarly, as shown in this Scheme, the initial step involves the condensation of aromatic aldehydes with malononitrile under the catalytic effect of the sulfonic acid-functionalized titanomagnetite NPs to produce the arylidenemalononitrile intermediate **I**. Subsequent nucleophilic addition of 3-methyl-1-phenyl-2-pyrazolin-5-one to the intermediate **I** followed successively by intramolecular cyclization to the intermediate **II**, and its rearrangement to furnish the 1,4-dihydropyrano[2,3-c]pyrazol-5-yl cyanide derivatives.

Catalyst Recyclability

The recyclability potential of the catalyst $Fe_{3-x}Ti_xO_4@SiO_3H$ MNPs was examined for the model reaction between 4-chlorobenzaldehyde, dimedone, and malononitrile. The recycling process involved the isolation of the catalyst from the reaction mixture simply by using an external magnet bar. The recovered catalyst was purified by washing with ethyl acetate followed by drying in an oven. The results shown in Fig. 4 indicate that the catalyst can be used for six consecutive times without noticeable loss of its activity. The integrity of the recovered catalyst was examined and proved to be as active as the original catalyst.

CONCLUSION

In summary, we have synthesized a highly effective and novel sulfonic acid-functionalized titanomagnetite nanoparticles ($Fe_{3-x}Ti_xO_4@SiO_3H$) as a versatile nano-catalyst which efficiently activates the one-pot three-component synthesis of tetrahydrobenzo[b]pyranes (4*H*-chromenes) and 1,4-dihydropyrano[2,3-c]pyrazol-5-yl cyanides. The structure of these nanoparticles was established by different analytical methods such as FT-IR, EDX and SEM analyses. The main advantages of the present protocol are efficiency, versatility, high yield, short reaction times, cleaner reaction profile, easy work-up, easy catalytic recyclability and reusability with no loss of activity that make this protocol highly useful and attractive in development of benign chemical processes and products.

EXPERIMENTAL

General

Chemicals were purchased from Merck chemical company. The ^{1}H and ^{13}C NMR spectra were recorded for samples in $CDCl_3$ or DSMO-d_6 on 90, 300 MHz and 400 MHz BRUKER spectrometers using Me_4Si as internal standard. Fourier transform infrared (FT-IR) spectra were recorded on a Shimadzu 435-U-04 FT spectrophotometer from KBr pellets. Melting points were measured on a BUCHI 510 apparatus in open capillary tubes. Scanning electron microscopy (SEM) was performed on a KYKY-EM3200 instrument operated at 26 kV accelerating voltage. Qualitative analysis of $Fe_{3-x}Ti_xO_4@SO_3H$ sample was performed by using energy dispersive X-ray fluorescence (EDXRF) spectroscopy (Brand: Link analytical XR300). Energy Dispersive X-ray analysis of the prepared catalyst was performed on a SEM-TESCAN MIRA3-FEG instrument. Ultrasonication was performed in a 2200 ETH-SONICA ultrasound cleaner with a frequency of 45 kHz.

Preparation Of The Catalyst $Fe_{3-X}ti_xo_4@SO_3H$ Nps

Preparation Of The Magnetic $Fe_{3-X}ti_xo_4$ Nps

Titanomagnetite nanoparticles were prepared based on almost a similar procedure as reported by Yang and co-workers.[55] $FeSO_4.7H_2O$ (1.903 g) was dissolved in deionised water (10 mL). The pH of the solution was reduced to < 1 by adding HCl solution. Then, $TiCl_4$ (0.75 mL) and hydrazine monohydrate (2 mL) were added respectively to the reaction mixture. The resulted mixture was refluxed at 90°C under N_2 atmosphere for 30 min. followed by dropwise addition of an aqueous solution of NaOH (1.6 g) and $NaNO_3$ (0.77 g) in deionised water (10 mL) under vigorous stirring at a rate of 500 rpm for 1 h. Finally, the resulting mixture was cooled to room temperature. The precipitated titanomagnetite nanoparticles were isolated in an external magnetic field simply by using a magnet bar, then washed with water several times and dried in air.

Preparation Of Sulfonic Acid-Functionalized $Fe_{3-X}ti_xo_4$ Mnps

The prepared $Fe_{3-x}Ti_xO_4$ MNPs (1 g) were dispersed in CH_2Cl_2 (15 mL) under ultrasonication for 30 min. Then, chlorosulfonic acid (1.5 mL) was added dropwise over a period of 2 h at room temperature under vigorous stirring at a rate of 500 rpm. After addition was completed, the resulting mixture was shaken for 1 h. The precipitated $Fe_{3-x}Ti_xO_4@SO_3H$ NPs were then magnetically isolated from the reaction mixture by a magnet bar. The isolated nanoparticles were consecutively washed with CH_2Cl_2 (3 ×5 mL) and EtOH (3 × 5 mL), and dried in air. The amount of SO_3H acid groups per one gram of the support determined via titration with 0.025 M NaOH solution was found to be in the range of 4.1-5.5 mmol.

Typical Procedure For The Synthesis Of 4H-Chromenes

To a mixture of aromatic aldehyde 1 (1 mmol), malononitrile (0.066 g, 1 mmol), and $Fe_{3-x}Ti_xO_4@SO_3H$ MNPs (0.03 g) in EtOH (5 mL) and H_2O (5 mL), was added dimedone (0.140 g, 1 mmol) and the resulting mixture was refluxed for an appropriate time (Table 3). After completion of the reaction as monitored by thin layer chromatography (TLC), the resulted reaction mixture was cooled to room temperature, diluted with hot ethanol (5 mL), and stirred for 10 min. Then, the catalyst was isolated in a magnetic field and the remaining supernatant was diluted with water (30 mL) and let to stir for 10 min. The precipitated product was filtered, washed with water, and dried in oven. Recrystallization of the crude product from EtOAc/*n*-hexane (1:3) provided pure product. All the synthesized products **2a-k** are known compounds which were characterized based on their melting points and spectral (FT-IR, ^{1}H NMR) data and compared with the reported corresponding data (Table 3).

Typical Procedure For The Synthesis Of 1,4-Dihydropyrano[2,3-C]Pyrazoles

To a mixture of aldehyde 1 (1 mmol), malononitrile (0.066 g, 1 mmol) and 3-methyl-1-phenyl-1H-pyrazol-5(4*H*)-one (0.174 g, 1 mmol), was added the catalyst $Fe_{3-x}Ti_xO_4@SO_3H$ MNPs (0.05 g) under stirring at 105°C for an appropriate time (Table 4). The progress of the reaction was monitored by TLC. After completion of the reaction, the mixture was diluted with hot ethanol (10 mL), and stirred for 10 min. The catalyst was isolated in an external magnetic field. The remaining supernatant was evaporated to leave the crude product which was purified by recrystallization from absolute EtOH. All the synthesized products **3a-i** are known compounds which were characterized by their melting points and spectral (FT-IR, ^{1}H NMR) analysis and compared with the reported corresponding data (Table 4).

SUPPORTING INFORMATION

Supplementary Material (FT-IR and ^{1}H NMR data) for this article can be accessed on the publisher's website.

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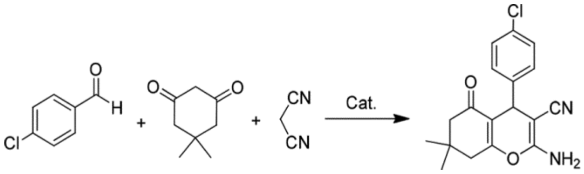
Table 1. Screening the reaction parameters for the model synthesis of 2-amino-4-(4-chlorophenyl)-7,7-dimethyl-5-oxo-5,6,7,8-tetrahydro-4*H*-chromene-3-carbonitrile[a].



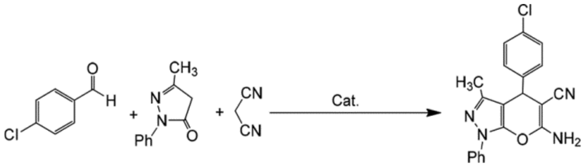
Entry	Catalyst (g)	Solvent[b]	Temperature (°C)	Time (min)	Yield (%)[c]
1	0.01	no solvent	r.t.	120	15
2	0.01	H_2O	r.t.	120	38
3	0.01	EtOH	r.t.	120	45
4	0.01	EtOH/H_2O	r.t.	60	62
5	0.01	EtOH/H_2O	50	60	68
6	0.01	EtOH/H_2O	reflux	60	76
7	0.01	EtOH/H_2O	reflux	30	74
8	0.03	EtOH/H_2O	reflux	60	95
9	0.05	EtOH/H_2O	reflux	60	95
10	0.08	EtOH/H_2O	reflux	60	95
11	0.05	EtOH/H_2O	reflux	30	92
12	no cat.	EtOH/H_2O	reflux	60	25

[a]Conditions: 4-chlorobenzaldehyde (1 mmol), 5,5-dimethyl-1,3- cyclohexanedione (1 mmol), malononitrile (1 mmol), solvent (6 mL).

[b] EtOH and H_2O were used in equal volumes of 3 mL each in the case of the mixed solvent EtOH/H_2O.

[c] Isolated pure yield.

Table 2. Screening the reaction parameters for the model synthesis of 6-amino-4-(4-cholrophenyl)-3-methyl-1-diphenyl-1,4-dihydropyrano[2,3-c]pyrazole-5-carbonitrile[a].

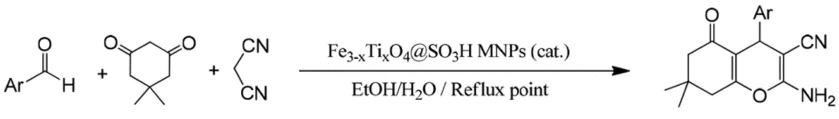


Entry	Catalyst (g)	solvent	Temperature (°C)	Time (min)	Yield (%)[b]
1	0.01	no solvent	r.t.	90	22
2	0.01	H_2O	r.t.	90	12
3	0.01	EtOH	r.t.	90	18
4	0.03	no solvent	r.t.	90	25
5	0.03	H_2O	r.t.	90	15
6	0.03	EtOH	r.t.	90	20
7	0.05	no solvent	r.t.	90	32
8	0.05	no solvent	50	90	48
9	0.05	no solvent	90	90	72
10	0.05	no solvent	105	90	96
11	0.05	no solvent	105	120	94
12	0.08	no solvent	105	90	95
13	no cat.	no solvent	105	90	trace

[a] Conditions: 4-chlorobenzaldehyde (1 mmol), malononitrile (1 mmol), 3-methyl-1-phenyl-2-pyrazolin-5-one (1 mmol), solvent (6 mL).

[b] Isolated pure yield.

Table 3. Synthesis of 4*H*-chromenes catalyzed by sulfonic acid-functionalized titanomagnetite $Fe_{3-x}Ti_xO_4@SiO_3H$ MNPs in $EtOH/H_2O$ at reflux point[a].



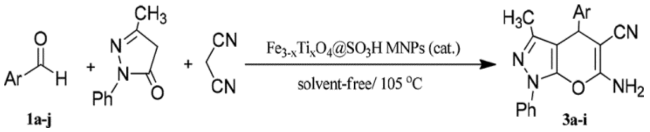
1a-k **2a-k**

Entry	Ar	Product	Time (min)	Yield (%)[b]	Mp (°C)	
					Found	Reported
1	C_6H_5	**2a**	60	95	236-238	235-238 [58]
2	$4\text{-}FC_6H_4$	**2b**	50	92	189-191	191-193 [59]
3	$4\text{-}MeC_6H_4$	**2c**	60	92	208-210	210-213 [60]
4	$2\text{-}MeOC_6H_4$	**2d**	50	93	203-205	203-205 [61]
5	$2,5\text{-}(MeO)_2C_6H_3$	**2e**	45	92	179-183	178-180 [62]
6	$4\text{-}ClC_6H_4$	**2f**	60	95	215-217	215-216 [46]
7	$2\text{-} ClC_6H_4$	**2g**	45	95	212-214	214-215 [59]
8	$3\text{-}ClC_6H_4$	**2h**	60	90	222-224	224-226 [62]
9	$3\text{-}NO_2C_6H_4$	**2i**	55	94	218-219	213-217 [63]
10	$4\text{-}NO_2C_6H_4$	**2j**	50	95	182-185	181-184 [63]
11	$4\text{-}HOC_6H_4$	**2k**	60	90	207-209	206-208 [64]

[a] Conditions: aldehyde (1 mmol), 5,5-dimethyl-1,3- cyclohexanedione (1 mmol), malononitrile (1 mmol), EtOH (3mL)/H_2O (3mL), catalyst (0.03 g), reflux temperature.

[b] Isolated pure yield.

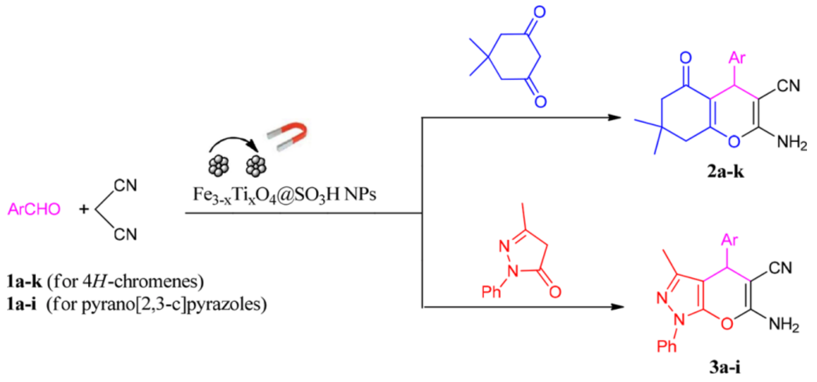
Table 4. Solvent-free synthesis of 1,4-dihydropyrano[2,3-c]pyrazoles catalyzed by sulfonic acid-functionalized titanomagnetite MNPs $Fe_{3-x}Ti_xO_4@SiO_3H^a$.



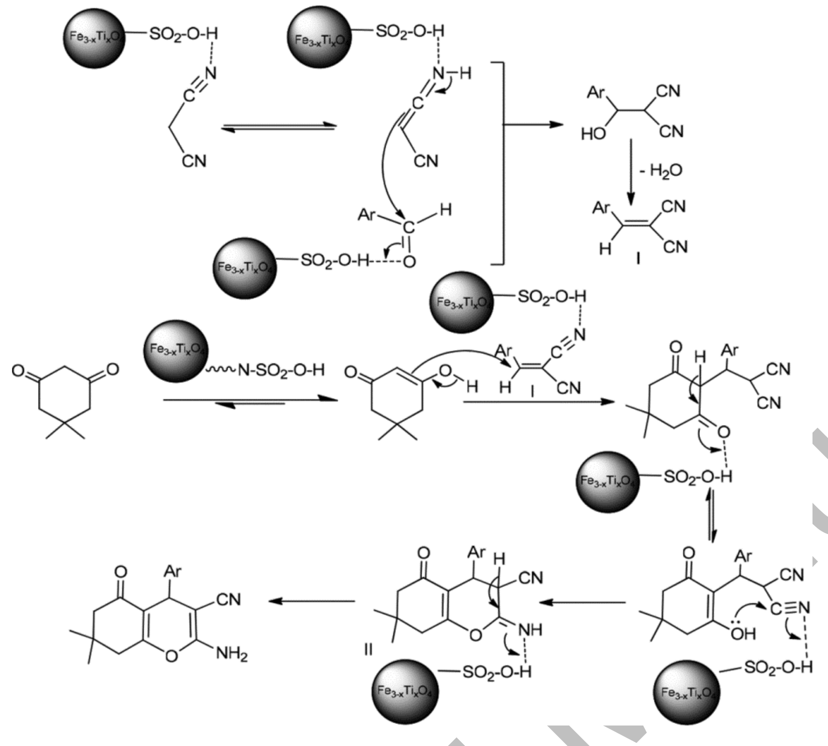
Entry	Ar	Product	Time (min)	Yield (%)[b]	Mp (˚C)	
					Found	Reported
1	Ph	**3a**	90	90	170-171	169-171 [65]
2	2-ClC_6H_4	**3b**	75	89	146-148	144-146 [66]
3	4-$MeOC_6H_4$	**3c**	90	89	178-180	177-178 [67]
4	4-ClC_6H_4	**3d**	90	96	184-187	186-187 [67]
5	4-FC_6H_4	**3e**	60	92	174-177	176-177 [67]
6	3-$NO_2C_6H_4$	**3f**	90	90	192-194	193-194 [66]
7	4-$NO_2C_6H_4$	**3g**	75	94	186-188	188-190 [68]
8	3-BrC_6H_4	**3h**	85	96	160-163	159-160 [69]
9	3-ClC_6H_4	**3i**	70	87	157-160	158-159 [65]

[a] Conditions: 4-chlorobenzaldehyde (1 mmol), malononitrile (1 mmol), 3-methyl-1-phenyl-2-pyrazolin-5-one (1 mmol), solvent-free, catalyst (0.05 g), 105˚C.

Scheme 1. Synthesis of 4*H*-chromenes and pyrano[2,3-c]pyrazoles catalyzed by $Fe_{3-x}Ti_xO_4@SO_3H$ nanoparticles.



Scheme 2. A possible reaction passway for the $Fe_{3-x}Ti_xO_4$@SiO_3H-catalyzed synthesis of tetrahydrobenzo[b]pyran derivatives.



Scheme 3. A possible reaction passway for the $Fe_{3-x}Ti_xO_4@SiO_3H$-catalyzed synthesis of 1,4-dihydropyrano[2,3-c]pyrazoles.

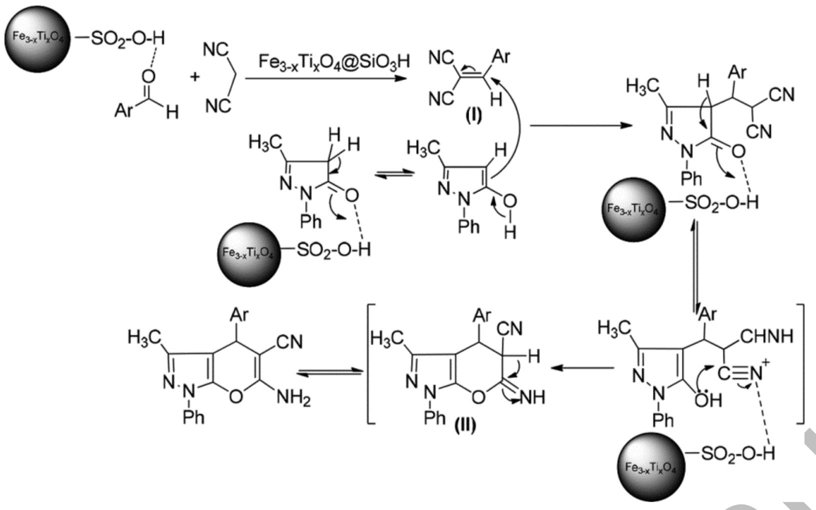


Fig. 1. FT-IR spectra of (a) $Fe_{3-x}Ti_xO_4$ NPs; (b) $Fe_{3-x}Ti_xO_4@SO_3H$ NPs

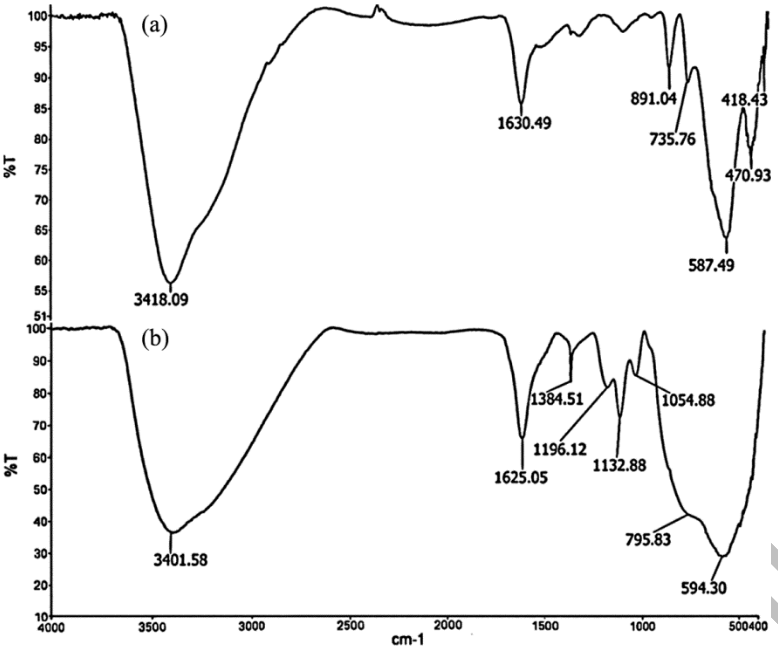


Fig. 2. EDX spectrum of titanomagnetite@SO_3H nanoparticles

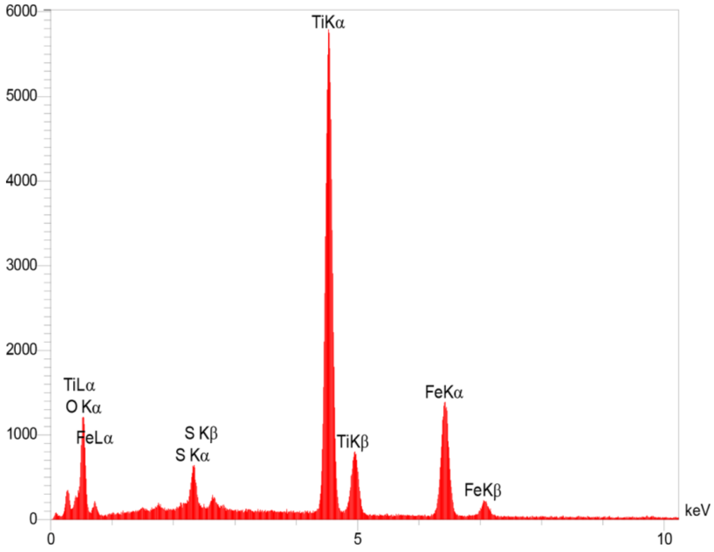


Fig. 3. SEM micrograph of titanomagnetite@SO_3H nanoparticles

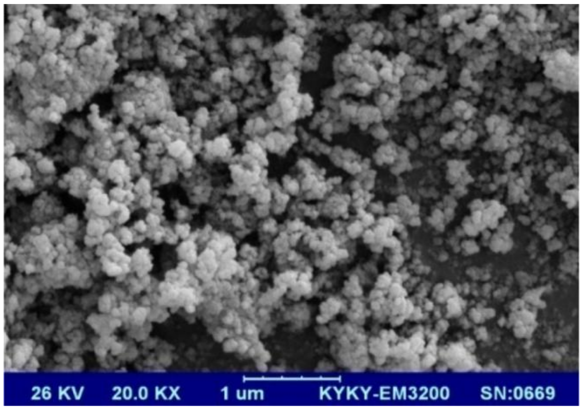


Fig. 4. Recyclability potential of the catalyst in the synthesis of benzo[b]pyrans