FULL PAPER

Preparation and characterization of nanomagnetic piperidinium benzene-1,3-disulfonate ionic liquid as a novel, green and heterogeneous catalyst and its use in the synthesis of 1*H*– pyrazolo[1,2-*b*]phthalazine-5,10-diones and 1*H*–pyrazolo[1,2-*a*] pyridazine-5,8-diones under solvent-free conditions

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Ramin Ghorbani-Vaghei, Faculty of Chemistry, Bu-Ali Sina University, Hamedan 6517838683, Iran. Email: rgvaghei@yahoo.com The one-pot four-component synthesis of 1H-pyrazolo[1,2-*b*]phthalazine-5,10diones and 1H-pyrazolo[1,2-*a*]pyridazine-5,8-diones was carried out from the reaction between various aldehydes, malononitrile, hydrazine hydrate and phthalic anhydride or maleic anhydride at 110 °C in solvent-free conditions using piperidinium benzene-1,3-disulfonate nanomagnetic ionic liquid (NMIL) as a novel and reusable catalyst. Some advantages of the presented procedure are a significant reduction in cost, effective catalysis and reusability of the catalyst. NMIL was thoroughly characterized using Fourier transform infrared spectroscopy, X-ray diffraction, scanning and transmission electron microscopies, thermogravimetry, derivative thermogravimetry, Brunauer–Emmett–Teller analysis, vibrating sample magnetometry and energy-dispersive X-ray spectroscopy. The technique is developed as a suitable and safe method for the synthesis of 1H-pyrazolo[1,2-*b*] phthalazine-5,10-diones and 1H-pyrazolo[1,2-*a*]pyridazine-5,8-diones making use of an efficient and reusable green catalyst.

KEYWORDS

1*H*–pyrazolo[1,2-*a*]pyridazine-5,8-diones, 1*H*–pyrazolo[1,2-*b*]phthalazine-5,10dione, magnetic nanoparticle ionic liquid (NMIL), piperidinium benzene-1,3disulfonate, solvent-free conditions

1 | INTRODUCTION

In recent years, heterogeneous catalysts have gained significance because of economic and environmental concerns.^[1–9] Among the various heterogeneous catalysts, particularly ionic liquids as homogeneous, heterogeneous and recyclable catalysts have attracted much attention in organic synthesis.^[10–12] To overcome some problems, such as high usage of ionic liquids in organic reactions, lack of economic efficiency, time-consuming processes for their recycling, which causes their waste, and separation from reaction vessel, which pollutes the environment, ionic liquids are often stabilized on magnetic nanoparticles (MNPs). This method causes an increase in activity and selectivity of these liquids in

organic reactions in addition to a decrease in their consumption. The ionic liquids stabilized on MNPs act as heterogeneous catalysts in organic reactions. These kinds of catalysts can be easily separated using a magnet and recycled after the end of the reaction. Based on these considerations, MNPs as heterogeneous catalysts have received considerable attention due to their interesting structures and prominent catalytic activities.^[13–18]

The synthesis of 1H-pyrazolo[1,2-*b*]phthalazine-5,10diones and 1H-pyrazolo[1,2-*a*]pyridazine-5,8-diones has attracted a great deal of attention because of their biological and pharmacological actions. Literature reports have already established that pyrazoles and phthalazines have various pharmacological properties such as anticancer,^[19,20] antifungal^[21,22] anti-inflammatory,^[23] antiviral,^[24] antidepressant,^[25] antibacterial,^[26] antipyretic^[27] and anticonvulsant^[28–30] activities. In this paper we present a new class of ionic liquid, namely piperidinium benzene-1,3-disulfonate nanomagnetic ionic liquid (NMIL; Scheme 1), as a simple, efficient and novel catalyst, which was successfully used as a catalyst in the solvent-free synthesis of 1*H*–pyrazolo[1,2*b*]phthalazine-5,10-diones and 1*H*–pyrazolo[1,2-*a*] pyridazine-5,8-diones via the one-pot four-component condensation reaction between various aldehydes, malononitrile, hydrazine hydrate and phthalic anhydride or maleic anhydride (Scheme 2).

2 | RESULTS AND DISCUSSION

A very effective one-pot synthesis was carried out of a variety of 1H-pyrazolo[1,2-*b*]phthalazine-5,10-diones and 1Hpyrazolo[1,2-*a*]pyridazine-5,8-diones catalysed by the piperidinium benzene-1,3-disulfonate magnetic nanoparticle ionic liquid under solvent-free conditions. High yields of products were achieved using a simple workup.

The structure of NMIL as an efficient, reusable and heterogeneous catalyst was characterized through various methods: Fourier transform infrared (FT-IR) spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), thermogravimetric analysis (TGA), derivative thermogravimetry (DTG), Brunauer–Emmett–Teller (BET) analysis, vibrating sample magnetometry (VSM) and energy-dispersive X-ray spectroscopy (EDX).

FT-IR spectroscopy was used to compare the produced Fe_3O_4 MNPs, SCMNPs and the other core-shell

surface-modified samples (Figure 1). The FT-IR spectrum of Fe₃O₄ MNPs shows a characteristic absorption peak of Fe–O bond at about 585 cm⁻¹. The absorption peaks of the silica shell in the spectrum of SCMNPs at around 1100 and 810 cm⁻¹ are ascribed to the antisymmetric and symmetric stretching vibrations of Si–O–Si in oxygen–silica tetrahedra, respectively. Moreover, the absorption peak of the SCMNPs-Pr-Cl core–shell MNPs at 2957 cm⁻¹ is connected to the stretching vibration of C–H groups. Additionally, the absorption band at 3408 cm⁻¹ is attributed to the stretching vibration of N–H of the piperidinium moiety and the peak appearing at 1645 cm⁻¹ is attributed to the stretching vibration of the C=C bonds of benzene-1,3-disulfonate. Also, the two peaks observed at 1220 and 1105 cm⁻¹ are related to the vibrational modes of the sulfonate groups.



SCHEME 2 Synthesis of 1*H*–pyrazolo[1,2-*b*]phthalazine-5,10-diones and 1*H*–pyrazolo[1,2-*a*]pyridazine-5,8-diones in the presence of NMIL catalyst





FIGURE 1 FT-IR spectra: (a) $Fe_3O_4@SiO_2$; (c) $Fe_3O_4@SiO_2@(CH_2)_3Cl$; (d) $Fe_3O_4@SiO_2@(CH_2)_3$ -piperidine; (e) $\{Fe_3O_4@SiO_2@(CH_2)_3-piperidine)\}_{2benzene-1,3-disulfonate}$

TGA and DTG curves of NMIL as a catalyst display the mass loss of organic material as it decomposes upon heating (Figure 2). The MNP catalyst demonstrates two-step weight loss behaviour. The weight loss from the NMIL catalyst (room temperature to 100 °C) is due to the removal of physically adsorbed water and organic solvents, which were applied in the process of synthesis of NMIL catalyst. The weight loss is about 12%. The main weight loss (70%) between 120 and 510 °C occurs mainly due to the thermal decomposition of the organic layer on the surface of MNPs. Therefore, in the temperature range between 100 and 510 °C, around 10% weight loss is observed confirming 0.25 mmol g⁻¹ organic groups loaded on the SCMNP surface.

The size, shape and morphology of the NMIL catalyst was investigated via XRD (Figure 3), and SEM and TEM imaging methods (Figure 4). Considering the intensity ratio of the main XRD peak detected at $2\theta = 35.60^{\circ}$, the crystalline structure of the magnetic ionic liquid catalyst can obviously be identified (Table 1). The average crystallite size D was determined using the Scherrer formula, $D = K\lambda/$ $(\beta \cos \theta)$, where K is the Scherrer constant, λ is the X-ray wavelength, β is the half-maximum peak width and θ is the Bragg diffraction angle. Consequently, the average size of the magnetic ionic liquid catalyst is found to be about 7.38-33.67 nm. For additional study for determination of particle size of the NMIL catalyst, we used SEM and TEM analyses. The shapes and dimensions of the particles can be seen in Figure 4. As expected, the SEM and TEM images of the NMIL catalyst indicate that the previous calculation of the particle size is quite accurate and is about 5-35 nm. Both SEM and TEM techniques corroborate the XRD patterns in

which nano-sized ionic liquid catalyst was shown using characteristic peaks. These results support our method for the synthesis of the NMIL catalyst. The XRD pattern of Fe₃O₄ is consistent with the patterns of spinel ferrites reported in the literature. The position and relative intensities of all peaks conform well with the standard XRD pattern of Fe₃O₄ MNPs (JCPDS card no. 85-1436), indicating the retention of the crystalline cubic spinel structure of MNPs. The XRD patterns of the particles display nine characteristic peaks linked to a cubic iron oxide phase $(2\theta = 14.80^\circ)$, 30.10°, 35.50°, 43.10°, 53.00°, 57.00°, 62.80°, 70.50°, 73.90°). These are assigned to the corresponding indices (1 1 0), (2 2 0), (3 1 1), (4 0 0), (3 3 1), (4 2 2), (5 1 1), (4 4 0) and (5 3 1), respectively. It is implicit that the resultant nanoparticles are pure Fe₃O₄ with a spinel structure and that the grafting process does not lead to any phase change of Fe₃O₄.

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EDX analysis of the synthesized NMIL catalyst indicates the probable elements in the structure of the catalyst, i.e. carbon, oxygen, nitrogen and sulfur (Figure 5).

Magnetic measurements of the Fe₃O₄ nanoparticles and NMIL catalyst were conducted at room temperature using VSM. Based on the magnetization curves, the saturation magnetization of the synthesized NMIL catalyst decreased from 60 emu g⁻¹ (Fe₃O₄) to 36 emu g⁻¹. This reduction in saturation magnetization is owing to the surface coating on the Fe₃O₄ MNPs (Figure 6).

To optimize reaction conditions, the condensation reaction of phthalic anhydride, hydrazine hydrate, 4-nitrobenzaldehyde and malononitrile was selected as a model reaction with various amounts of nanomagnetic catalyst in



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FIGURE 2 (a) TGA and DTG curves of NMIL catalyst; (b) TGA of Fe₃O₄@SiO₂@(CH₂)₃Cl (I); (c) TGA of piperidine (II)

the range 25–130 °C under solvent-free conditions (Table 2). The best results are achieved when the reaction is conducted using 20 mg of nanomagnetic catalyst at 110 °C (Table 2, entry 10). No improvement is detected in the yield of reaction on increasing the amount of the catalyst and temperature (Table 2, entries 11-13). It is evident that in the absence of the nanomagnetic catalyst, the product yield is zero or very low (Table 2, entries 1 and 2).

To compare the results for various conditions and solvents, the reaction of phthalic anhydride, hydrazine hydrate, 4-nitrobenzaldehyde and malononitrile was used as a model with 20 mg of NMIL catalyst in a variety of solvents such as H₂O, C₂H₅OH, CH₃CN, CH₃CO₂Et, CH₂Cl₂ and toluene under solvent-free conditions at 110 °C. The results are summarized in Table 3. As is evident, no solvent is obviously the best selection for this reaction. Another advantage of choosing solvent-free conditions for this reaction is the safety, and benignity in comparison with organic cheapness solvents.

Encouraged by the important results obtained, and with the purpose of exhibiting an overview and determining the scope of this method, a range of 1Hpyrazolo[1,2-*b*]phthalazine-5,10-diones were synthesized from the one-pot four-component reaction between phthalic anhydride, malononitrile, hydrazine hydrate and numerous aldehydes with a catalytic amount of NMIL catalyst (20 mg) under solvent-free conditions at 110 °C. The results are summarized in Table 4. The reaction time for aromatic aldehydes is rather faster than that for aliphatic aldehydes. Also, aromatic aldehydes having electron-withdrawing groups react rather faster than those having electron-donating groups. Though metaand para-substituted aromatic aldehydes give very good results, ortho-substituted aromatic aldehydes produce rather lower yields because of steric effects.

In another experiment, the recyclability and reusability of the NMIL catalyst were confirmed using the condensation of 4-chlorobenzaldehyde with malononitrile, ethyl acetoacetate and hydrazine hydrate. At the end of the reaction, the catalyst was separated using an external supermagnet, and then the reaction mixture was decanted and washed with water. Afterwards the NMIL was reused for consecutive catalytic runs under similar experimental conditions. We found that the catalytic activity of the catalyst was maintained within the limits of experimental error for seven consecutive runs (Figure 7). Also, TGA of the NMIL catalyst before and after recycling shows the thermal stability of the catalyst.

Nitrogen adsorption-desorption measurements were conducted to investigate the BET specific surface area of the materials (Figure 8a,b). The BET surface area of the NMIL is 79.4 m² g⁻¹ (total pore volume = 0.246 cm³ g⁻¹; mean pore diameter = 12.37 nm), and its pore size distribution is plotted in Figure 8(d). The achieved surface area for Fe_3O_4 NNPs is 10.9 m² g⁻¹ (total pore volume = $0.047 \text{ cm}^3 \text{ g}^{-1}$; mean pore diameter = 17.25 nm), and its pore size distribution to plotted in Figure 8(c). In comparison to Fe₃O₄ MNPs, the BET surface area of the NMIL catalyst is greater. The specific surface area of the NMIL catalyst increases owing to coating of Fe₃O₄ MNPs with grafted organic tags (Figure 8). The higher surface area of the prepared catalyst in comparison to Fe₃O₄ MNPs core can be stated as one of the benefits of this catalyst. The pore sizes of both samples are chiefly between 1 and 10 nm, which indicates that the samples include both micropores and mesopores.



FIGURE 3 XRD patterns: (a) Fe_3O_4 (b) Fe_3O_4 (c) Fe_3O_4 (c) F

To compare the efficacy of $\{Fe_3O_4@SiO_2@(CH_2)_3-piperidinium\}_2$ benzene-1,3-disulfonate catalyst with those of Fe_3O_4 , $Fe_3O_4@SiO_2$, $Fe_3O_4@SiO_2@(CH_2)_3Cl$ and $Fe_3O_4@SiO_2@(CH_2)_3$ -piperidine in the synthesis of 1Hpyrazolo[1,2-*b*]phthalazine-5,10-diones, we used these catalysts in the condensation of 4-nitrobenzaldehyde, phthalic anhydride, malononitrile and hydrazine hydrate. The results are summarized in Table 5. The NMIL catalyst strongly improves the synthesis of 1H-pyrazolo[1,2-*b*]phthalazine-5,10-diones in terms of both reaction time and isolated yield. The reaction times are shorter and the yields are higher when the MNPs catalyst is used.

A possible mechanism for the synthesis of 1H-pyrazolo[1,2-*b*]phthalazine-5,10-diones (**5**) is shown in Scheme S3 (supporting information).^[33] Firstly, NMIL catalyst activates the carbonyl group of phthalic anhydride (**1**) and then hydrazine hydrate attacks the oxygen ester group which affords phthalhydrazide (**6**). In the next step, NMIL catalyst activates the carbonyl group of aldehyde (**4**) and malononitrile (**3**). Malononitrile rearranges and then attacks the carbonyl group of the activated aldehyde which affords

2-benzylidenemalononitrile (8). Finally, phthalhydrazide produced in the previous step attacks the 2-benzylidenemalononitrile which is activated by NMIL. After intramolecular attack takes place, the expected 1H-pyrazolo[1,2-*b*]phthalazine-5,10-diones are produced as shown in Scheme S3 (supporting information).^[32,34]

In continuation, we investigated the synthesis of 1H-pyrazolo[1,2-*b*]phthalazine-5,10-diones in the presence of nanomagnetic catalyst. The efficiency of this catalyst is comparable to that of some other reported catalysts (Table 6). Using our catalyst in the synthesis of 1H-pyrazolo[1,2-*b*] phthalazine-5,10-diones gives the best results for this reaction.

3 | CONCLUSIONS

We have reported an efficient and green process for the one-pot four-component synthesis of 1H-pyrazolo[1,2-*b*]phthalazine-5,10-diones and 1H-pyrazolo[1,2-*a*]pyridazine-5,8-diones from the reaction between various aldehydes, malononitrile,



FIGURE 4 (a, b) SEM images and (c, d) TEM images of new NMIL catalyst

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TABLE 1 XRD data for NMIL catalyst

Entry	2θ (°)	Peak width (FWHM) (°)	Size (nm)	Interplanar distance (nm)
1	22.80	0.58	13.97	0.389564
2	25.70	0.35	23.28	0.346225
3	35.60	1.13	7.38	0.251885
4	62.80	0.73	12.75	0.147990
5	71.10	0.29	33.67	0.132436







FIGURE 5 EDX of MNPs with (a) piperidinium benzene-1,3-disulfonate ionic liquid, (b) Fe₃O₄@SiO₂@(CH₂)₃Cl (I) and (c) piperidine (II)

hydrazine hydrate and phthalic anhydride or maleic anhydride in the presence of a catalytic amount of NMIL as an effective, novel, efficient and powerful nanomagnetic ionic liquid with good to excellent yields under solvent-free conditions at 110 °C. The NMIL catalyst was thoroughly characterized using FT-IR spectroscopy, XRD, SEM, TEM, TGA, DTG, BET analysis, VSM and EDX. The chief advantages of this procedure are the simplicity of the workup and the products can be isolated without



FIGURE 6 VSM analysis of NMIL catalyst in comparison with Fe₃O₄ MNPs

TABLE 2 Effect of quantity of catalyst and temperature on synthesis of 1Hpyrazolo[1,2-*b*]phthalazine-5,10-diones under solvent-free conditions^a

Entry	Catalyst loading (mg)	Reaction temperature (°C)	Reaction time (min)	Yield (%) ^b
1	_	r.t.	120	—
2	_	110	120	5
3	5	r.t.	50	35
4	5	110	50	45
5	10	r.t.	50	45
6	10	100	50	65
7	10	110	45	70
8	20	r.t.	45	60
9	20	100	45	85
10	20	110	45	94
11	20	130	45	94
12	30	110	45	94
13	30	130	45	94

^aReaction conditions: phthalic anhydride (1 mmol), hydrazine hydrate (1.2 mmol), 4-nitrobenzaldehyde (1 mmol) and malononitrile (1 mmol).

^bIsolated yield

^bIsolated yield.

TABLE 3 Effect of solvents on synthesis of 1H-pyrazolo[1,2-b]phthalazine-5,10-diones at 110° C^a

Entry	Solvent	Reaction time (min)	Yield (%) ^b
1	Solvent-free	45	94
2	H_2O	50	88
3	C ₂ H ₅ OH	50	90
4	CH ₃ CO ₂ Et	90	60
5	CH ₃ CN	90	65
6	CH_2Cl_2	120	10
7	Toluene	120	5

^aReaction conditions: phthalic anhydride (1 mmol), hydrazine hydrate (1.2 mmol), 4-nitrobenzaldehyde (1 mmol) and malononitrile (1 mmol).

chromatography. We propose that the technique has also numerous benefits such as low consumption of catalyst and clean reaction, which make it an appropriate and significant approach for the synthesis of 1H-pyrazolo[1,2-*b*] phthalazine-5,10-diones and 1H-pyrazolo[1,2-*a*]pyridazine-5,8-diones.

4 | EXPERIMENTAL

4.1 | Preparation of NMIL Catalyst

Firstly, magnetite-phase Fe₃O₄ was prepared by adding 3 ml of FeCl₃ (2 M; dissolved in 2 M HCl) to 10.33 ml of doubledistilled water followed by dropwise addition of 2 ml of Na₂SO₃ (1 M) for 3 min under magnetic stirring. When the solution colour changed from red to light yellow, 80 ml of an NH₃·H₂O solution (0.85 M) was added under vigorous stirring. After 30 min, the precipitate of magnetite Fe_3O_4 was washed to pH < 7.5 with distilled water and separated with an external magnet. To 1 g of Fe₃O₄ were added 20 ml of water, 80 ml of ethanol, 3 ml of ammonia and 3 ml of tetraethylorthosilicate (TEOS) under reflux to achieve $Fe_3O_4@SiO_2$.^[25-28] Subsequently, 3 g of $Fe_3O_4@SiO_2$ and (3-chloropropyl)triethoxysilane (10 mmol) in 80 ml of dry toluene were refluxed under nitrogen for 12 h. The obtained Fe₃O₄@SiO₂@(CH₂)₃Cl was filtered, washed twice with dry toluene and anhydrous diethyl ether, and dried at 80 °C for 6 h in vacuum. To synthesize piperidine-modified MNPs (pi-SCMNPs), 1.0 g pf silica-coated MNPs was added to 50 ml of dry toluene and 3 ml of piperidine. The reaction mixture was dispersed for 30 min, and then refluxed with stirring for 72 h. The solid phase was filtered, washed with toluene and ethanol, and dried at 60 °C in vacuum (Scheme 1).

$H_{2}N'_{2}^{NH_{2}}$					
Entry	Aldehyde	Product	Reaction time (min)	Yield (%) ^b	M.p. (°C)
1	3-Phenylpropanal	6a	80	80 (275 mg)	241-243 ^[31]
2	2-Naphthaldehyde	6b	65	84 (307 mg)	266-268 ^[32]
3	3,4,5-Trimethoxybenzaldehyde	6c	80	75 (304 mg)	248-250 ^[31]
4	3-Bromobenzaldehyde	6d	40	90 (354 mg)	266-268 ^[33]
5	2-Methoxybenzaldehyde	6e	60	80 (277 mg)	250–252 ^[33]
6	4-Fluorobenzaldehyde	6f	40	92 (307 mg)	263–265 ^[32]
7	2-Chlorobenzaldehyde	6 g	45	86 (301 mg)	255-256 ^[33]
8	2,3-Dichlorobenzaldehyde	6 h	40	86 (330 mg)	274-276 ^[34]
9	2-Fluorobenzaldehyde	6i	45	88 (294 mg)	266–268 ^[35]
10	2-Nitrobenzaldehyde	6j	45	88 (318 mg)	260-262 ^[33]
11	2-Bromobenzaldehyde	6 k	45	87 (343 mg)	267-268 ^[32]
12	4-Bromobenzaldehyde	61	40	92 (362 mg)	274-276 ^[33]
13	2,6-Dichlorobenzaldehyde	6 m	40	86 (330 mg)	275-277 ^[34]
14	2,4-Dichlorobenzaldehyde	6n	40	85 (326 mg)	233-235 ^[34]
15	4-Nitrobenzaldehyde	60	40	94 (339 mg)	256-258 ^[35]
16	3-Chlorobenzaldehyde	6р	40	87 (304 mg)	255-257 ^[33]
17	3-Methoxybenzaldehyde	6q	60	82 (284 mg)	253-255 ^[32]
18	3-Nitrobenzaldehyde	6r	40	90 (325 mg)	255-257 ^[33]
19	Benzaldehyde	6 s	55	82 (259 mg)	224-226 ^[33]
20	4-Chlorobenzaldehyde	6 t	40	90 (315 mg)	254-256 ^[35]
21	2-Bromobenzaldehyde	7a	60	88 (302 mg)	288-290 ^[29]
22	2-Methoxybenzaldehyde	7b	85	60 (178 mg)	259-261[29]
23	2-Chlorobenzaldehyde	7c	70	84 (252 mg)	272-274 ^[29]
24	3-Chlorobenzaldehyde	7d	70	82 (246 mg)	277-279 ^[29]
25	2,4-Dichlorobenzaldehyde	7e	65	80 (267 mg)	274-276 ^[29]
26	2.6 Diablarahanzaldahuda	76	70	80 (267	274 276[29]

TABLE 4 Synthesis of 1H-pyrazolo[1,2-b]phthalazine-5,10-diones and 1H-pyrazolo[1,2-a]pyridazine-5,8-diones using 20 mg of NMIL catalyst^a

^aReaction conditions: aldehyde (1 mmol), malononitrile (1 mmol), phthalic anhydride or maleic anhydride (1 mmol), hydrazine hydrate (1.2 mmol), solvent free, 110 °C. ^bIsolated yield.

An amount of 1.0 g of pi-SCMNPs was suspended in 50 ml of acetonitrile and 3 ml of benzene-1,3-disulfonic acid was added to this suspension. The mixture was stirred at room temperature for 24 h, then filtered and washed twice with acetonitrile and further washed with deionized water and dried at 60 °C in vacuum^[33] (Scheme 1).

4.2 | General procedure for preparation of 1*H*– Pyrazolo[1,2-*b*]phthalazine-5,10-diones

A mixture of phthalic anhydride (1 mmol, 0.148 g), NMIL (20 mg) and hydrazine hydrate (1.2 mmol, 0.038 g, 0.038 ml) was stirred under solvent-free conditions at 110 °C for 20 min to form phthalhydrazide as intermediate.

Then, to this reaction were added aldehyde (1 mmol) and malononitrile (1 mmol, 0.077 g), and the mixture was stirred for a specified time. The reaction was monitored using TLC (*n*-hexane–ethyl acetate, 7:3). After the reaction was complete, cold water was added to the reaction mixture and the catalyst was separated magnetically. The Fe₃O₄ MNPs were washed three to four times with ethanol and then dried at 50 °C for 3 h in order to preserve the catalyst for used in subsequent reactions. The products in the aqueous layer were filtered, separated and then washed with hot ethanol. The obtained products were characterized using TLC and FT-IR and NMR spectroscopies. In this study, NMIL as a catalyst was recycled and reused seven times without any loss of catalytic activity.



FIGURE 7 (a) Reusability of NMIL catalyst in 40 min. (b) TGA of NMIL catalyst after seven recycles



 $\label{eq:FIGURE 8} \begin{array}{l} (a, b) \mbox{ BET nitrogen adsorption-desorption isotherms and (c, d)} \\ \mbox{pore size distributions of (a, c) Fe_3O_4 MNPs and (b, d) NMIL catalyst} \end{array}$



 TABLE 5
 Comparison of efficiency of MNPs catalyst with that of other catalysts in the reaction of 4-nitrobenzaldehyde, phthalic anhydride, malononitrile and hydrazine hydrate^a

Entry	Catalyst	Catalyst loading (mg)	Time (min)	Yield (%) ^b
1	MNPs catalyst	20	45	94
2	Fe ₃ O ₄	20	120	25
3	Fe ₃ O ₄ @SiO ₂	20	120	20
4	Fe ₃ O ₄ @SiO ₂ @(CH ₂) ₃ Cl	20	120	5
5	Fe ₃ O ₄ @SiO ₂ @(CH ₂) ₃ -piperidine	20	120	5

^aReaction conditions: 4-nitrobenzaldehyde (1 mmol), phthalic anhydride (1 mmol), hydrazine hydrate (1 mmol), malononitrile (1 mmol), solvent-free, 110 °C.

^bIsolated yield.

TABLE 6 Comparison of catalytic activity of various catalysts for the synthesis of 1H-pyrazolo[1,2-*b*]phthalazine-5,10-diones^a

Entry	Catalyst	Reaction time (min)	Yield (%)
1	InCl ₃ (30 mmol)	120	84 ^[36]
2	MnCl ₂ (10 mol%)	240	76 ^[37]
3	$ZnCl_2{\cdot}4H_2O~(10~mol\%)$	240	80 ^[37]
4	NiCl ₂ ·6H ₂ O (10 mol%)	240	85 ^[37]
5	$CoCl_2{\cdot}6H_2O~(10~mol\%)$	240	81[37]
6	NMIL (0.5 mol%)	45	88

^aReaction conditions: phthalic anhydride (1 mmol), hydrazine hydrate (1.2 mmol), 2-nitrobenzaldehyde (1 mmol) and malononitrile (1 mmol).

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