Inorganic Chemistry Communications 94 (2018) 80–84

Contents lists available at ScienceDirect

Inorganic Chemistry Communications

journal homepage: www.elsevier.com/locate/inoche

Short communication

Isoreticular interpenetrated pillared-layer microporous metal-organic framework as a highly effective catalyst for three-component synthesis of pyrano[2,3-*d*]pyrimidines

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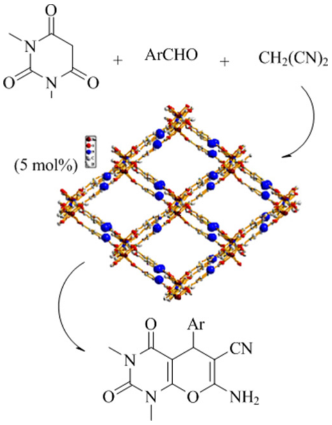
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Microporous
Metal-organic framework
Catalyst
Three-component reaction

ABSTRACT

Two isoreticular microporous Zn(II)-MOFs, $[Zn_2(NH_2\text{-}BDC)_2(4\text{-bpdh})]\cdot 3DMF$ (TMU-16-NH_2) and $[Zn_2(BDC)_2(4\text{-bpdh})]\cdot 3DMF$ (TMU-16), (NH_2-BDC = amino-1,4-benzenedicarboxylate, BDC = 1,4-benzenedicarboxylate and 4-bpdh = 2,5-bis(4-pyridyl)-3,4-diaza-2,4-hexadiene) were used as heterogeneous catalysts. The TMU-16-NH_2 was used as an efficient heterogeneous base catalyst for the three-component cyclocondensation of 1,3-dimethylbarbituric acid, aryl aldehydes and malononitrile, giving rise to pyrano[2,3-*d*]pyrimidines. The ease of catalyst synthesis, excellent conversions and reusability of the catalyst for five consecutive cycles without a significant degradation in its catalytic activity, suggests significant future potential of this metal-organic framework for a wide range of base catalyzed reactions.

Metal–organic frameworks are crystalline compounds consisting of infinite lattices built up of the inorganic secondary building unit (SBU, metal ions, or clusters) and organic linkers, connected by coordination bonds of moderate strength. MOFs contain three well-differentiated parts where the catalytic function can be allocated: the metallic component, the organic linker, and the pore space [1]. These materials have shown a variety of enormous potential applications including (but not limited to) gas adsorption [2], separations [3], luminescent [4], drug

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https://doi.org/10.1016/j.inoche.2018.06.002
Received 7 April 2018; Received in revised form 26 May 2018; Accepted 1 June 2018

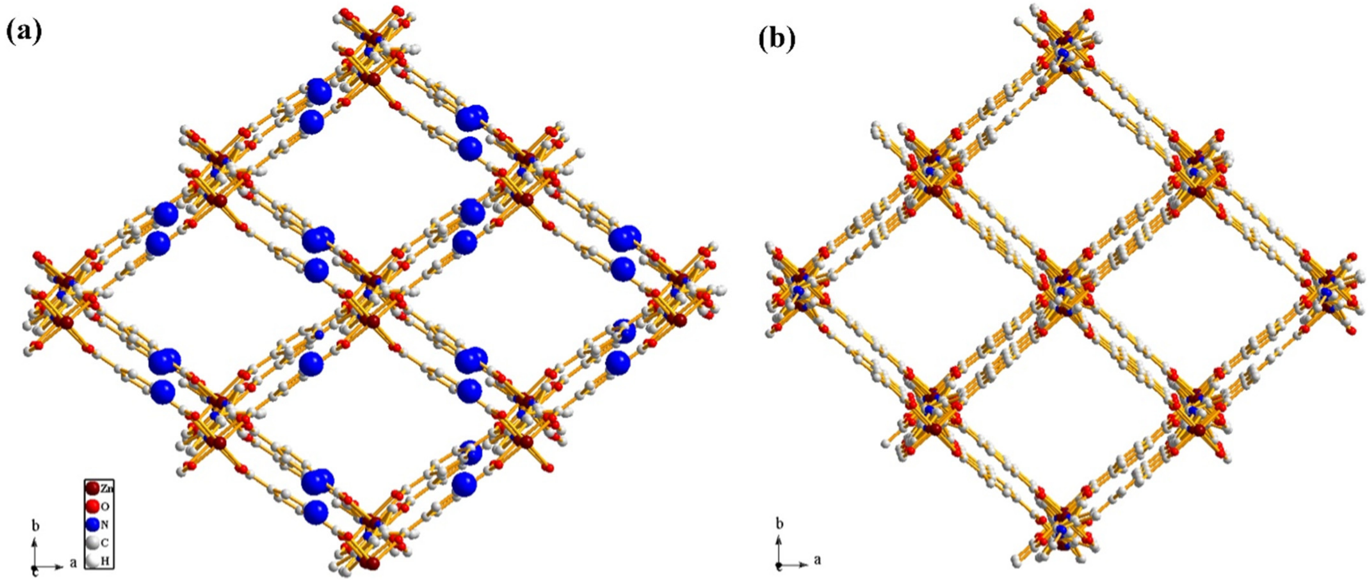


Fig. 1. Representations of the two-fold interpenetration (a) TMU-16-NH_2, highlighting the amine groups and (b) TMU-16, which contain 1D channels of 3 Å, viewed along the rectangular diagonal of the paddle-wheel clusters. All hydrogen atoms and the disordered guest molecules are omitted for clarity.

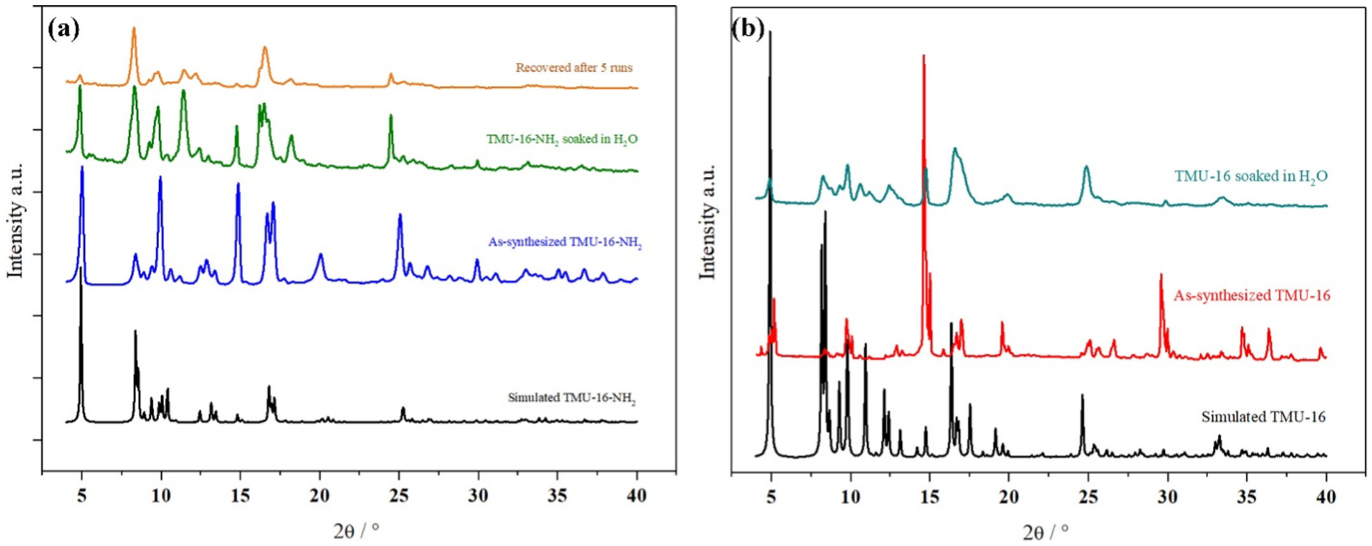


Fig. 2. PXRD of (a) TMU-16-NH_2: simulated (black), as-synthesized (blue), immersed in water for 2 h (green), and recovered after five runs, (b) TMU-16: simulated (black), as-synthesized (red), and immersed in water for 2 h (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

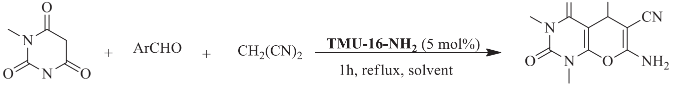
delivery [5] and sensing [6]. Over the last few years, abundant examples in literature have demonstrated the potential of MOFs in catalysis [7–11]. 4*H*-Pyrans and pyrimidinones are very important organic compounds with a wide range of biological activities. These compounds are reported to possess significant antibacterial, anticoagulant, anticancer, spasmolytic, diuretic, antianaphylactic, antihypertensive and anti-inflammatory activities [12–18]. On the other hand, pyrano[2,3-*d*] pyrimidines have received considerable attention over the past years due to their wide range of the diverse pharmacological action such as antitumor, cardiotonic, hepatoprotective, antihypertensive and antibronchitic activity [19–23]. These compounds are generally synthesized via a one-pot three-component cyclocondensation of 1,3-dimethylbarbituric acid, aryl aldehydes and malononitrile in the presence of several catalysts such as 1,8-diazabicyclo[5.4.0]undec-7-ene [24], MgO [25], PEG-stabilized Ni nanoparticles [26], $ZnFe_2O_4$ nanoparticles [27], KF [28] and Mn/ZrO_2 [29]. Synthesis of these compounds using microwave irradiation [30] and electrocatalytic procedure in the presence of sodium bromide as electrolyte [31] have been also reported. However, most of these methodologies suffer from disadvantages such as unsatisfactory yields, long reaction times and the use of relatively expensive catalysts. These finding prompted us toward further investigation in search for a new catalyst which will carry out the synthesis of these compounds under simpler experimental set up and eco-friendly conditions [32]. Continuing to our previous work [33], in this work we wish to report the utilization of isostructural two-fold interpenetrated microporous metal-organic framework, $[Zn_2(NH_2\text{-}BDC)_2(4\text{-bpdh})]\cdot 3DMF$ (TMU-16-NH_2) as an efficient heterogeneous catalyst for the condensation of 1,3-dimethylbarbituric acid, aryl aldehydes and malononitrile to achieve biologically interest Pyrano[2,3-*d*]pyrimidines. TMU-16-NH_2 is a pillared-layer MOFs like those was reported previously [34–37]. High catalytic activity was observed and catalyst could be reused without significant degradation in activity. Avoiding the utilization of harmful solvents in this environmentally friendly process is particularly appealing.

$[Zn_2(NH_2\text{-}BDC)_2(4\text{-bpdh})]\cdot 3DMF$ (TMU-16-NH_2) is a two-fold interpenetrated pillared-layer microporous Zn-MOF [38, 39]. TMU-16-NH_2 is composed of paddle-wheel dinuclear zinc carboxylate units $Zn_2(COO)_4$, which are bridged by the NH_2-BDC ligands to form a distorted 2D square grid. The 2D square grids are pillared by 4-bpdh molecules to form a 3D framework with a topology that can be described as a primitive cubic lattice (RCSR symbol pcu) [38, 39]. Two of the 3D frameworks interpenetrate in TMU-16-NH_2, reducing the pore size resulted in a 1D channel in the direction of the rectangular diagonal of the paddle-wheel clusters with a cross section of approximately 3.1 × 3.2 Å in cross section (including van der Waals radii) (Fig. 1a) [38]. Furthermore to investigate the influence of amine group on the catalytic activity, the pores in the MOF became free of reactive groups (-NH_2) without changing the SBU or the underlying framework topology. The non-functionalized isoreticular framework, $[Zn_2(BDC)_2(4\text{-bpdh})]\cdot 3DMF$ (TMU-16) was used as another heterogeneous catalyst (Fig. 1b). TMU-16 and TMU-16-NH_2 are isostructural and crystallize in the monoclinic space group C2/c [38]. The phase purity of the bulk materials were independently confirmed by powder X-ray diffraction (PXRD). The powder X-ray diffraction data show that the two compounds are isotypic to each other (Fig. 2). The comparison of the calculated free volume of the compounds by PLATON shows that it varies in decrements from 3648.4 $Å^3$ per unit cell (42.7% of the cell volume) in TMU-16 to 2286.1 $Å^3$ (27.6%) in TMU-16-NH_2 [40].

TGA data indicate that TMU-16-NH_2 and TMU-16 release their guest molecules over the temperature ranges 25–230 and 25–280 °C to form the guest-free phases, $[Zn_2(NH_2\text{-}BDC)_2(4\text{-bpdh})]$ and $[Zn_2(BDC)_2(4\text{-bpdh})]$, respectively (Fig. S1 in the SI). Weight losses of about 23% were measured for both MOFs, which are attributed to the loss of 3DMF (calc.: ~24%). The networks TMU-16-NH_2 and TMU-16 are thermally stable up to 320 and 360 °C, respectively, as evidenced by the fact that no additional weight loss was observed at those temperatures, after which the frameworks eventually decompose.

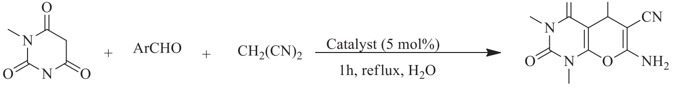
To characterize the possible catalytic behavior of TMU-16-NH_2, three component reaction of 1,3-dimethylbarbituric acid, benzaldehyde and malononitrile, in the presence of TMU-16-NH_2 in different solvents was performed. It can be deduced from these results that higher yields were achieved in polar protic solvents, whereas the reaction occurred with difficulty in solvents with lower polarity (Table 1). Methanol and ethanol are more polar than acetonitrile. As a result, the reaction efficiency is higher in these solvents. However, the reactions under solvent-free condition were slow. It should be pointed out that in the absence of catalyst, the reaction was slow and even after prolonged reaction time, considerable amounts of starting materials remained unreacted. Catalytic activity of TMU-16-NH_2 is as a result of -NH_2 and azine groups in its structure. The results of applying TMU-16 in three component reaction of 1,3-dimethylbarbituric acid, benzaldehyde and malononitrile approved this and indicate that the catalytic activity decreased in the absence of -NH_2 group (Table 2). TMU-16-NH_2 unlike IRMOF-3, is stable in water (Fig. 2a) and the reaction in the presence of TMU-16-NH_2 that was carried out in water, proceeded to 96% yield after 1 h. To examine the general application of the catalyst (TMU-16-NH_2), we extended the scope of the reaction to the synthesis of various Pyrano[2,3-*d*]pyrimidines under the above-mentioned optimized conditions (Table 3). These reactions proceeded smoothly and no undesirable side reactions were observed. Both electron donating and withdrawing groups on the phenyl ring were well tolerated affording the expected products in good yields. Substrates with electron withdrawing substituents are more reactive in the reaction, because they are more reactive toward nucleophilic attack. As a result, yield of the reaction in the presence of them is higher. In addition, TMU-16-NH_2 could be reused at least 5 runs without any loss in its activity (Fig. 3). So that powder PXRD (Fig. 2) the FT-IR data (Fig. 4) data showed no changes in its structure. Thus the integrity of the framework is confirmed.

Table 1
The one-pot three component reaction of benzaldehyde, malononitrile and 1,3-dimethylbarbituric acid in different solvents.



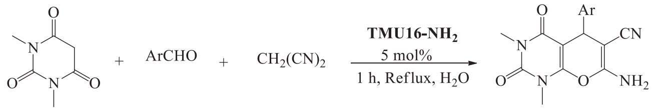
Entry	Solvent	Yield (%)
1	EtOH	96
2	MeOH	85
3	H_2O	98
4	n-Hexane	4
5	CH_3CN	42
6	Toluene	16
7	–	10

Table 2
The reaction in the presence of TMU-16 and TMU-16-NH_2.



Entry	Catalyst	Yield (%)
1	TMU-16	40
2	**TMU-16-NH_2**	**98**
3	–	0

Table 3
The reaction in the presence of TMU-16 and TMU-16-NH_2.



Entry	Ar	Yield (%)	M.p. (°C)	Reported
			Found	
1	C_6H_5	98	216–218	219–220
2	4-MeO-C_6H_4	84	221–223	225–226
3	4-Br-C_6H_4	86	231–233	235
4	4-NO_2-C_6H_4	100	214–216	217–219
5	4-Cl-C_6H_4	90	198–200	200
6	2-NO_2-C_6H_4	100	202–204	206
7	3-NO_2-C_6H_4	100	204–206	204–206

In summary, two MOFs, $Zn(NH_2\text{-}BDC)(4\text{-bpdh})]\cdot 2DMF$ (TMU-16-

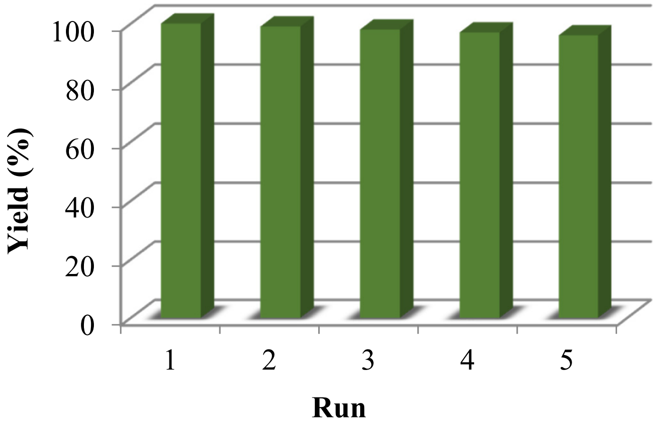


Fig. 3. Recyclability of TMU-16-NH_2 in the reaction.

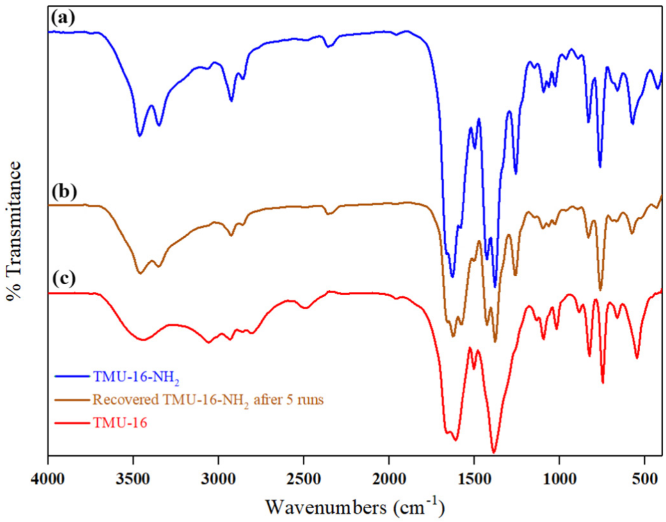


Fig. 4. FT-IR spectra of (a) as-synthesized TMU-16-NH$_2$, (b) recovered TMU-16-NH$_2$ after five runs and (c) as-synthesized TMU-16.

NH$_2$) and [Zn(BDC)(4-bpdh)]·2DMF (TMU-16), were used as heterogeneous catalysts. These two MOFs can be used as solid catalysts for selective synthesis of Pyrano[2,3-*d*]pyrimidines. The reaction in the presence of TMU-16-NH$_2$ is faster because of basic –NH$_2$ group in its structure. No contribution from leached active species present in the liquid phase was detected. The catalyst can be easily separated from the reaction mixture by simple decantation, and can be reused several times without a significant degradation in its activity, thus offering a route to green chemistry transformations.

Acknowledgements

Support of this investigation by Iran National Science Foundation under grant number 93035544 is gratefully acknowledged. The authors also would like to acknowledge the financial support of Tarbiat Modares University and Iran University of Science and Technology for supporting this investigation.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.inoche.2018.06.002.

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