An interpenetrating amine-functionalized metal–organic framework as an efficient and reusable catalyst for the selective synthesis of tetrahydro-chromenes†

Vahid Safarifard,‡ Saeideh Beheshti‡ and Ali Morsali*

The amine group of the 2-amino-1,4-benzenedicarboxylic acid (NH₂-BDC) ligand in a novel two-fold interpenetrated metal–organic framework, [Zn(NH₂-BDC)(4-bpdb)]2DMF (TMU-17-NH₂) has been found to be a base catalyst active site. TMU-17-NH₂ consists of both NH₂-BDC and the N,N'-bipyridine-type rigid linkers (4-bpdb = 1,4-bis(4-pyridyl)-2,3-diaza-2,3-butadiene) with ZnN₂O₄ secondary building units (SBUs). The MOF was characterized by FT-IR spectroscopy, elemental analysis, powder X-ray diffraction, thermal gravimetric analysis and single-crystal X-ray diffraction. The amine-functionalized framework was used as an efficient heterogeneous base catalyst for the synthesis of tetrahydro-chromenes. Excellent conversions were obtained under mild conditions in the presence of 6 mol% catalyst. The TMU-17-NH₂ catalyst could be reused several times without significant degradation in catalytic activity.

Introduction

Metal–organic frameworks (MOFs) are a new class of hybrid crystalline materials composed of organic linkers and metal nodes, with a diversity of structural characteristics and the nature of the pore surface. The ability to synthesize a wide range of MOFs has made them attractive materials for application in gas adsorption,† separation,‡ luminescence,§ drug delivery and sensing. The most important advantage of MOFs with respect to other functional materials is the targeted preparation of the MOFs by considering the specific linkers for certain applications. In particular, MOFs represent ideal candidates for heterogeneous catalysts by introducing catalytic sites.

Tetrahydrobenzob[b]pyrans have recently attracted considerable interest as an important class of heterocycles having a broad spectrum of biological properties, such as anticoagulant, diuretic, anticancer and antianaphylactic activities. Various synthetic methods have been reported for promoting the preparation of tetrahydrobenzob[b]pyrans; for example, microwave, ultrasound, organic solvents such as DME, use of hexadeceyldimethylenzyl ammonium bromide, tetrabutylammonium bromide, ionic liquids, rare earth perfluorooctanoate, MgO, lipase, diammonium hydrogen phosphate, silica bonded n-propyl-4-aza-1-azoniabicyclo[2.2.2]octane chloride and DBU. However, most of these methods suffer from certain drawbacks, such as application of expensive non-reusable catalysts, long reaction times, toxic solvents and tedious work-up procedures. Therefore, to avoid these limitations, a great deal of effort is being directed to develop an efficient catalytic system for synthesis of these compounds. In the present study, we wish to report the utilization of a mixed-ligand two-fold interpenetrated metal–organic framework, [Zn(NH₂-BDC)(4-bpdb)]2DMF (TMU-17-NH₂) as an efficient heterogeneous catalyst for the condensation of aldehyde, dimesdone and malononitrile for the preparation of biologically interesting tetrahydro-chromenes. Moreover, to investigate the influence of the amine group on the catalytic activity, 1,4-benzenedicarboxylate (BDC) was selected as a surrogate for NH₂-BDC to synthesize the amine free isoreticular framework, [Zn(BDC)(4-bpdb)]2DMF (TMU-17, Scheme 1).

Scheme 1  Schematic view of the comparative syntheses for TMU-17-NH₂ and TMU-17.
high catalytic activity was observed in the case of the amine-functionalized framework and the catalyst could be reused without significant degradation in activity. Avoiding the utilization of harmful solvents in this environmentally friendly process is particularly appealing.

**Experimental**

**Materials and measurements**

Starting reagents for the synthesis were purchased and used without further purification from commercial suppliers (Sigma-Aldrich, Merck and others). Elemental analysis (carbon, hydrogen, and nitrogen) was performed using an ECS 4010 CHNSO made by Costech, Italy. The infrared spectra were recorded on a Nicolet Fourier Transform IR, Nicolet 100 spectrometer in the range of 500–4000 cm⁻¹ using the KBr disk technique. Thermogravimetric analyses (TGA) of the compounds were performed using a computer-controlled PL-DTA STA 1500 apparatus. Single-phase powder samples of compounds were prepared using a Philips X’pert diffractometer with monochromated Cu Kα radiation (λ = 1.54056 Å). The simulated XRD powder pattern based on single crystal data was prepared using Mercury software.22 GC runs were performed using an Echrom GC A90 gas chromatograph.

**Synthetic procedures**

**Preparation of 1,4-bis[4-pyridyl]-2,3-diaza-2,3-butadiene (4-bpdb).** 4-bpdb was synthesized according to the synthesis route reported in the literature.17 1 mL (11 mmol) of hydrazine was added dropwise to a solution of pyridine-4-carboxaldehyde (2.2 mL, 22 mmol) dissolved in ethanol (15 mL). Two drops of formic acid were added and the mixture was stirred at room temperature for 24 h. The yellow solid that formed was filtered and washed several times with ethanol–ether (1:1). Yield, 79%.

**Preparation of [Zn(NH2-BDC)(4-bpdb)]-2DMF (TMU-17-NH2).** Zn(NO3)2·6H2O (0.297 g, 1 mmol), 4-bpdb (0.210 g, 1 mmol) and H2BDC·NH2 (0.181 g, 1 mmol) were dissolved in 15 ml of DMF. The mixture was placed in a Teflon reactor and heated at 80 °C for 3 days, and then it was gradually cooled to room temperature over 24 h. The yellow powder was obtained in a 38% yield. Elemental microanalysis for [Zn(BDC)(4-bpdb)]-2DMF, calculated (%): C, 51.46; H, 4.82; N, 16.16. Found (%): C, 52.47; H, 4.74; N, 15.50. FT-IR (cm⁻¹): 3462.05 (s), 3364.90 (s), 1676.84 (vs), 1609.95 (vs), 1574.38 (vs), 1425.94 (vs), 1380.69 (vs), 1253.26 (s), 1094.03 (m), 1014.26 (m), 830.72 (s), 772.04 (s), 749.62 (s), 688.44 (s), 525.69 (s).

**General procedure for the synthesis of tetrahydro-4H-chromenes.** To a mixture of dimedone (1 mmol), aldehyde (1 mmol) and malononitrile (1.5 mmol), 6 mol% of the catalyst was added in different solvents such as ethanol, methanol, H2O, n-hexane, acetonitrile, and toluene. The resulting mixture was stirred under reflux conditions for 4 h. The course of the reaction was followed by GC analysis. The reaction mixture was diluted with 5 mL of CH2Cl2. On completion of the reaction, the catalyst was recovered by centrifugation and the supernatant liquid was collected and evaporated to dryness. Pure product was obtained by recrystallization from EtOH. The catalyst was washed repeatedly with EtOAc, dried and reused when required.

**Crystallographic data collection and refinement.** Crystallographic measurements of compound TMU-17-NH2 were made using a Bruker APEX area-detector diffractometer. The intensity data were collected using graphite monochromated Mo Kα radiation (λ = 0.71073 Å) at 180 K. Cell parameters were retrieved using SMART software and refined with SAINT on all observed reflections.23 Data reduction was performed with the SAINT software. Absorption corrections were applied with the program SADABS.24 The structure was solved by direct methods with SHELXS-97.24 The refinement and all further calculations were carried out with SHELXL-97.24 The N- and C-bound H-atoms were included in calculated positions and treated as riding atoms. The non-H atoms were refined anisotropically, using weighted full-matrix least-squares on F². Crystallographic data and details of data collections and structure refinements of compound TMU-17-NH2 are listed in Table 1.

**Results and discussion**

Using the long, rigid bipyridyl-based ligand 1,4-bis(4-pyridyl)-2,3-diaza-2,3-butadiene (4-bpdb), linear amino-1,4-benzenedicarboxylate (NH2-BDC) and Zn(NO3)2 as a [Zn(NH2-BDC)(4-bpdb)]-2DMF (TMU-17-NH2) MOF was designed to have a 3D framework with pores that can be tuned by double interpenetration to have 1D channels. The pyridyl-based spacer can act as a pillar to link the metal-carboxylate layer to produce higher dimensional crystalline novel topological frameworks containing channels or cavities.25 There are considerable numbers of functional porous coordination compounds which have been prepared using 4-bpdb as a neutral azine or azo chromophore containing a bipyridyl ligand, in combination
with a dicarboxylate using the pillar-layer technique. Furthermore, to investigate the influence of the amine group on the catalytic activity, the pores in the MOF became free of reactive groups (–NH2), without changing the SBU and the underlying framework topology. Replacing NH2-BDC with BDC readily generates crystalline products of an amine free isostructural lattice, namely, TMU-17, which can be formulated as Zn(BDC)(4-bpdb) in its guest-free form.

A guest-filled phase, TMU-17-NH2, was synthesized by the solvothermal reaction of NH2-BDC, 4-bpdb, and Zn(NO3)2·6H2O in DMF at 80 °C for 72 h, and isolated as brown block-shaped crystals. The analogue, TMU-17, was synthesized using BDC under the same conditions but at a higher temperature, 115 °C. The formula of the compound was determined to be [Zn(NH2-BDC)(4-bpdb)]2DMF, for TMU-17-NH2, by elemental microanalysis and single-crystal X-ray diffraction studies. TMU-17 has been characterized by several techniques, including X-ray diffraction, TGA, FT-IR and elemental analysis. Although the atomic coordinates of the structure of TMU-17 are not currently available from single-crystal X-ray diffraction (because of the poor quality of the diffraction), its phase identity and purity were reliably confirmed by preliminary diffraction data, which provided cell parameter information. The available diffraction data gives a monoclinic cell (25.0% of the cell volume) by PLATON.30

Table 1 Crystal data and structure refinements for compound TMU-17-NH2

<table>
<thead>
<tr>
<th>Identification code</th>
<th>TMU-17-NH2</th>
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<tr>
<td>Chemical formula</td>
<td>C21H28N4O8Zn</td>
</tr>
<tr>
<td>Formula mass</td>
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</tr>
<tr>
<td>T (K)</td>
<td>180(2)</td>
</tr>
<tr>
<td>Crystal syst.</td>
<td>Monoclinic</td>
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<tr>
<td>Space group</td>
<td>C2/c</td>
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<tr>
<td>a (Å)</td>
<td>15.655(3)</td>
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<tr>
<td>b (Å)</td>
<td>16.561(3)</td>
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<tr>
<td>c (Å)</td>
<td>21.200(3)</td>
</tr>
<tr>
<td>β (deg)</td>
<td>120.567(9)</td>
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<tr>
<td>V (Å3)</td>
<td>4732.6(14)</td>
</tr>
<tr>
<td>Z</td>
<td>8</td>
</tr>
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</table>

$I_1 = \sum |F_o| - |F_c|/\sum |F_o|$, $b$ $wR_2 = (\sum w(F_o^2 - |F_c|^2)/\sum w(F_o^2))^1/2$.

The FT-IR spectrum of the compound TMU-17-NH2 shows the characteristic bands of the dicarboxylate groups of the NH2-BDC ligands at 1609 and 1380 cm⁻¹ for the asymmetric and symmetric vibrations, respectively, similar to the spectrum of TMU-17 which shows the asymmetric and symmetric vibrations bands of the dicarboxylate groups at 1609 and 1387 cm⁻¹, respectively (Fig. 1 right). The splitting of $v_{asym}(\text{CO}_2)$ in compounds TMU-17-NH2 and TMU-17 confirms that the carboxylate groups have the same coordination modes,26 in agreement with the crystal structure of TMU-17-NH2. The absence of the expected characteristic bands at 1730–1690 cm⁻¹ for the protonated carboxylate groups indicates the complete deprotonation of amino-1,4-benzenedicarboxylic acid and 1,4-benzedicarboxylic acid in the reaction with Zn ions.

TGA experiments indicate that both TMU-17-NH2 and TMU-17 release their guest molecules over the temperature range of ~25–270 °C to form the guest-free phases, [Zn(NH2-BDC)(4-bpdb)] and [Zn(BDC)(4-bpdb)], respectively, which clearly distinguishes them from other MOF materials such as IRMOF-3 (which has a decomposition temperature nearly 100 °C higher)27 (see Fig. S1 and S2†). Weight losses of about 25% were measured for both MOFs, which are attributed to the loss of 2 DMF molecules (calc.: ~24%). All of the aforementioned data support the hypothesis that TMU-17 is an analogue of TMU-17-NH2 with BDC present as a surrogate for NH2-BDC.

TMU-17-NH2 crystallizes in the monoclinic space group C2c. Single-crystal X-ray diffraction shows in TMU-17-NH2, the Zn center has a distorted octahedral coordination geometry (ZnN2O4), with two oxygen donors of one chelating bis-bidentate carboxylate group [Zn1–O3b = 2.339(6) Å, Zn1–O4b = 2.108(5) Å] and two oxygen donors of two bridging bidentate carboxylate groups in the horizontal direction [Zn1–O1 = 2.025(5) Å, Zn1–O2a = 2.012(4) Å]. The coordination sphere is completed by two nitrogen donors of 1,4-bis(4-pyridyl)-2,3-diaza-2,3-butadiene (4-bpdb) [Zn1–N1 = 2.164(5) Å, Zn1–N4d = 2.172(5) Å] in the axial direction (Fig. 2). The coordination mode in compound TMU-17-NH2 generates a cuboidal building block (Fig. 3a). Each corner of the cuboidal block is occupied by a binuclear subunit and the Zn⋯Zn separation in the binuclear subunit is 3.99 Å. Eight NH2-BDC ligands form the length and width of the cuboidal block while eight 4-bpdb ligands make up the height. The aggregation of the building blocks results in a 3D framework, and the 3D networks interlock with each other displaying a twofold interpenetrating mode (Fig. 3b and S3†). The calculated free volume in fully desolvated TMU-17-NH2 is 1184.3 Å³ per unit cell (25.0% of the cell volume) by PLATON.30 TMU-17-NH2 has 1D narrow channels of approximately 5.3 × 2.0 Å in cross.
section (including van der Waals radii) that are not large enough to be, in principle, accessible for N\textsubscript{2} (kinetic diameter for N\textsubscript{2}: 3.75 Å) adsorption. Also, the BET measurement showed that the framework is nonporous.

To characterize the possible catalytic behavior of the amine-functionalized TMU-17-NH\textsubscript{2}, a three component reaction of benzaldehyde, malononitrile, and dimedone in the presence of TMU-17-NH\textsubscript{2} in different solvents was performed. It can be deduced from the results that higher yields were achieved in polar protic solvents, whereas the reaction occurred with difficulty in solvents with lower polarity (Table 2). However, the reactions under solvent-free conditions were slow. It should be pointed out that in the absence of catalyst, the reaction was slow and even after a prolonged reaction time, considerable amounts of starting material remained unreacted. Catalytic activity of TMU-17-NH\textsubscript{2} is as a result of –NH\textsubscript{2} and also the azine groups in the structure. The results of applying the amine free framework of TMU-17 in a three component reaction of benzaldehyde, malononitrile, and dimedone confirmed this and indicate that the catalytic activity decreased in the absence of amine functionality (43% yield, Table S2†). TMU-17-NH\textsubscript{2}, unlike IRMOF-3, is stable in water and the reaction in the presence of TMU-17-NH\textsubscript{2}, that was carried out in water, proceeded to 75% yield after 4 h. Given the structures of the products, which seemingly require a space of 10–15 Å, it is obvious that the reactions are not occurring in the narrow channels of TMU-17-NH\textsubscript{2}. In agreement with the BET result that shows the MOFs are nonporous, it is suggested that the catalytic sites at the surface of the MOF are catalyzing the reaction.

To examine the general application of the catalyst (TMU-17-NH\textsubscript{2}), we extended the scope of the reaction to the synthesis of various tetrahydro-4\textsubscript{H}-chromenes 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.

In addition, TMU-17-NH\textsubscript{2} could be reused for at least 5 runs without any loss in its activity (Fig. 4). The integrity of the framework is confirmed by the FT-IR and the PXRD data (Fig. S4–S6 in the ESI†).

### Table 2 The one-pot three component reaction of benzaldehyde, malononitrile and dimedone in different solvents

<table>
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<th>Entry</th>
<th>Solvent</th>
<th>Yield (%)</th>
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<tr>
<td>1</td>
<td>EtOH</td>
<td>92</td>
</tr>
<tr>
<td>2</td>
<td>H\textsubscript{2}O</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>MeOH</td>
<td>64</td>
</tr>
<tr>
<td>4</td>
<td>CH\textsubscript{3}CN</td>
<td>32</td>
</tr>
<tr>
<td>5</td>
<td>Toluene</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>n-Hexane</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>—</td>
<td>35</td>
</tr>
</tbody>
</table>

### Table 3 The reaction in the presence of TMU-17-NH\textsubscript{2}

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ar</th>
<th>Yield (%)</th>
<th>M.p. (°C)</th>
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<tbody>
<tr>
<td>1</td>
<td>C\textsubscript{6}H\textsubscript{5}</td>
<td>92</td>
<td>228–230</td>
</tr>
<tr>
<td>2</td>
<td>2-MeO–C\textsubscript{6}H\textsubscript{4}</td>
<td>94</td>
<td>194–196</td>
</tr>
<tr>
<td>3</td>
<td>4-Me–C\textsubscript{6}H\textsubscript{4}</td>
<td>84</td>
<td>212–214</td>
</tr>
<tr>
<td>4</td>
<td>4-NO\textsubscript{2}–C\textsubscript{6}H\textsubscript{4}</td>
<td>96</td>
<td>177–180</td>
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<tr>
<td>5</td>
<td>2-Cl–C\textsubscript{6}H\textsubscript{4}</td>
<td>90</td>
<td>218–221</td>
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<tr>
<td>6</td>
<td>4-Me–N\textsubscript{2}–C\textsubscript{6}H\textsubscript{4}</td>
<td>80</td>
<td>210–213</td>
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<tr>
<td>7</td>
<td>3-NO\textsubscript{2}–C\textsubscript{6}H\textsubscript{4}</td>
<td>96</td>
<td>207–210</td>
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Fig. 2 View of the dimetal unit of TMU-17-NH\textsubscript{2}, hydrogen atoms have been omitted; symmetry codes: a = 1 – x, 1 – y, 1 – z; b = 0.5 – x, 0.5 + y, 0.5 – z; c = 0.5 + x, 0.5 – y, 0.5 + z; d = 1 + x, y, z; e = 2 – x, 1 – y, 1 – z.

Fig. 3 (a) Structure of the cuboidal block of TMU-17-NH\textsubscript{2}, showing Zn units linked by eight amino-1,4-benzenedicarboxylate anions and eight 1,4-bis(4-pyridyl)-2,3-diaza-2,3-butadiene units; (b) representations of the structure of the open phase TMU-17-NH\textsubscript{2} which contains 1D channels of 5.3 × 2.0 Å, viewed along the b axes. The two interpenetrating frameworks are shown in blue and green. The disordered guest molecules are omitted for clarity.

Fig. 4 View of the dimetal unit of TMU-17-NH\textsubscript{2}, hydrogen atoms have been omitted; symmetry codes: a = 1 – x, 1 – y, 1 – z; b = 0.5 – x, 0.5 + y, 0.5 – z; c = 0.5 + x, 0.5 – y, 0.5 + z; d = 1 + x, y, z; e = 2 – x, 1 – y, 1 – z.
To further verify the heterogeneity of system, a procedure similar to that of Sheldon et al. was performed for **TMU-17-NH$_2$**. After the reaction mixture was stirred for 1 hour, removal of the catalyst via filtration resulted in the complete shutdown of the reaction and hence, the system is totally heterogeneous in nature with no leaching under the reaction conditions (Fig. S7 in the ESI†).

**Conclusions**

In this work, an amine-functionalized MOF, [Zn(NH$_2$)$_2$BDC]2DMF (TMU-17-NH$_2$), and its isostructural non-functionalized MOF (i.e., [Zn(BDC)]2DMF TMU-17) were synthesized and their performances as solid base catalysts were investigated. Both of the MOFs showed catalytic activity caused by the azine group of the 4-bpdb pillar linker. The reaction in the presence of **TMU-17-NH$_2$** is faster because of the 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 at least five times without a significant degradation in its activity, thus offering a route to green chemistry transformations. Clearly, the amine modified MOF material holds great potential as a base catalyst.

**Acknowledgements**

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**Notes and references**

26. (a) R. Dey, B. Bhattacharya, P. Pachfule, R. Banerjee and D. Ghoshal, *CrystEngComm*, 2014, 16, 2305; (b) B. Bhattacharya, R. Haldar, R. Dey, T. K. Maji and...


