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ARTICLE TYPE

# Conversion of primary amines into secondary amines on a metal-organic framework using a tandem post-synthetic modification

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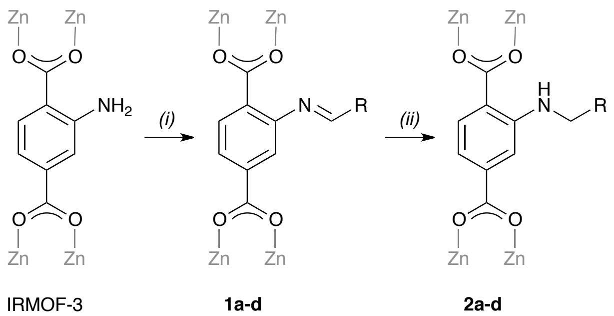
**The amine-functionalised metal-organic framework (MOF) [$Zn_4O(bdc\text{-}NH_2)_3$] (IRMOF-3, bdc-$NH_2$ = 2-amino-1,4-benzenedicarboxylate) has been post-synthetically modified in a tandem condensation-reduction process into secondary amine-containing MOFs. The degree of modification is enhanced by introduction of methanol, which helps to remove boron-containing side-products from the pores.**

Metal-organic frameworks (MOFs) are a relatively new class of crystalline solid-state material consisting of metal ions or aggregates that are connected by organic bridging linkers to form one-, two- or three-dimensional network structures.[1] Many MOFs exhibit permanent porosity, and as such they have attracted considerable attention for a wide range of applications including hydrogen storage, carbon sequestration and heterogeneous catalysis.[2]

The properties of MOFs are often enhanced by tailoring the pore surfaces with particular functional groups. However, this can be synthetically challenging as many desired functionalities are intolerant of the reaction conditions needed for MOF synthesis. One approach to functionalised MOF formation that has recently attracted considerable attention is post-synthetic modification (PSM),[3] as this allows required groups to be added to a pre-formed MOF. In order for PSM to be feasible, a chemically reactive 'tag' group[4] that can undergo conversion into another functionality generally needs to be present. The most commonly used tag in MOF PSM studies to date is the amine group, and conversions into a range of other functionalities including amides,[5, 6] ureas[7] and azides[8] have been achieved. Tandem modifications, in which the product from a PSM reaction becomes the starting material for a second PSM reaction have also been developed,[9] and these further broaden the synthetic potential of PSM protocols.

Post-synthetic conversions of amines into imines have been previously reported,[10] and used to anchor catalytically-active exo-framework metal centres into MOFs.[11] A wide range of aldehydes are readily available, so the conversion of an amine into an imine is very versatile, though with ethanal as a reagent hemiaminals and aziridines have also been reported as products.[12] Imines are susceptible to hydrolysis, so insufficiently robust for many potential applications. We sought to improve the stability of the functionalised MOFs by reducing the imine to a secondary amine. This type of tandem modification has been mentioned briefly in a review article,[13] but to the best of our knowledge full details have not been reported. Post-synthetic formation of secondary amine-functionalised MOFs have been reported through ring-opening reactions with sultones and aziridines,[14] and reaction with an alkyl bromide,[15] though both these approaches have limitations. In this communication we report our initial results using [$Zn_4O(bdc\text{-}NH_2)_3$] (IRMOF-3, bdc-$NH_2$ = 2-amino-1,4-benzenedicarboxylate).[16] Parallel experiments with [$Zn_2(bdc\text{-}NH_2)_2(dabco)$] (dabco = 1,4-diazabicyclo[2.2.2]octane)[17] led to negligible conversions and are not detailed further.

Preliminary reactions were carried out in THF at room temperature, as an initial solvent screen suggested this gave the best solubilities for the reagents and the highest conversions, while retaining the MOF crystallinity. The aldehyde RCHO (R = Me, Et, Pr, $C_7H_{15}$) was allowed to react with IRMOF-3 in THF at room temperature for 24 h, before adding $NaBH_3CN$ to the reaction mixture, which was then left for a further 48 h‡. The anticipated condensation-reduction process is summarised in Scheme 1.




**Scheme 1.** *(i)* RCHO, THF; *(ii)* $NaBH_3CN$, THF [R = Me (**1a**, **2a**), Et (**1b**, **2b**), Pr (**1c**, **2c**), $C_7H_{15}$ (**1d**, **2d**)].

After this time, the solid product was isolated by decantation and washed with fresh anhydrous THF. Powder X-ray diffraction confirmed that the bulk structure was unchanged by this process, with no significant changes observed in the powder patterns.

The degree of conversion into the products was calculated from the $^1H$ NMR spectra of products digested in $DCl/D_2O/d_6$-DMSO.[18] The dicarboxylic acids $H_2$bdc-NHEt, $H_2$bdc-NHPr, $H_2$bdc-NHBu and $H_2$bdc-$NHC_8H_{17}$ were prepared by analogous reactions on $H_2$bdc-$NH_2$, and used to help interpret the $^1H$ NMR spectra as both $H_2$bdc-$NH_2$ and $H_2$bdc-NHR (R = Et, Pr, Bu, $C_8H_{17}$) contain two sets of doublets and one set of doublets of doublets in the aromatic region. The alkyl region provides a clear

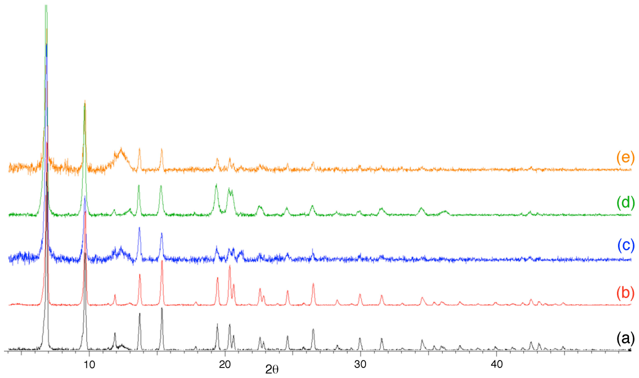



**Figure 1.** Powder X-ray diffraction patterns for (a) IRMOF-3, the product from the reaction between IRMOF-3, EtCHO and $NaBH_3CN$ in (a) THF at 293 K, (c) THF at 323 K, (d) THF-MeOH (15:1) at 293 K and (e) THF-MeOH (15:1) at 323 K .

way of identifying the secondary amine through the multiplicity of the signal for the hydrogen atoms on the β-carbon atom. Thus, a triplet is observed for $H_2$bdc-NHEt (from **2a**), a sextet for $H_2$bdc-NHPr (from **2b**), and quintets for $H_2$bdc-Bu (from **2c**) and $H_2$bdc-NH$C_8H_{17}$ (from **2d**).

The results are summarised in Table 1. In all cases, the spectra for the digested products of the reactions in THF revealed the presence of $H_2$bdc-$NH_2$ and $H_2$bdc-NHR, though for **2b-d** one or more by-products are also present. With the exception of the reaction with MeCHO, conversion is less than 10%.

| R | IRMOF-3 / % | by-products / % | **2** / % |
|---|---|---|---|
| Me (**2a**) | 67 | 0 | 33 |
| Et (**2b**) | 43 | 52 | 5 |
| Pr (**2c**) | 61 | 31 | 8 |
| $C_7H_{15}$ (**2d**) | 81 | 10 | 9 |

**Table 1.** Conversion of IRMOF-3 into the secondary amine-functionalised MOFs **2a-d** at room temperature in THF after 3d.

Neither continuation of the reaction for a longer period nor addition of further $NaBH_3CN$ significantly changed the ratio of products. Notably, no imine (**1a-d**) was observed in the $^1$H NMR spectra, though it is likely that any imine present would be hydrolysed in the MOF digestion, so $^1$H NMR spectroscopy cannot distinguish unreacted IRMOF-3 from **1a-d**.

One possible explanation for the poor conversion in the tandem PSM process is pore blocking by the reduction side-products. To confirm this, $^{11}$B NMR spectra were recorded on the digested MOFs, and these indicated the presence of a trigonal boron-containing species at δ 22 ppm (Fig. S26, ESI). The poor solubility of this side-product in THF means it cannot be washed out of the pores using this solvent. Suspecting that the side-product would have greater solubility in MeOH, the reactions were repeated using mixtures of THF and MeOH (15:1) as the solvent. The products were isolated and analysed in the same way as those from the reactions in THF. Powder X-ray diffraction patterns (Fig. 1) revealed that the MOF networks were unchanged during the course of the reactions. The results from the digestion studies are summarised in Table 2 and a typical $^1$H NMR spectrum is shown in Fig. 2 (the other spectra are provided in the ESI).

The results clearly demonstrate that the presence of MeOH

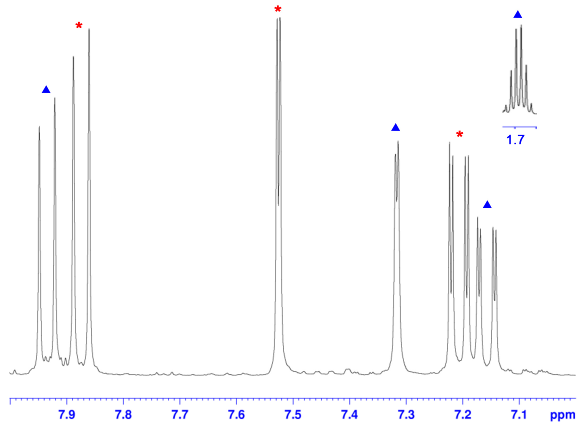



**Figure 2.** $^1$H NMR spectrum of the digested product from the reaction between IRMOF-3, EtCHO and $NaBH_3CN$ in THF-EtOH (15:1). The red asterisks denote $H_2$bdc-$NH_2$ derived from IRMOF-3, and the blue triangles denote $H_2$bdc-NHPr derived from **2b**. The inset shows the β-carbon methylene group – observation of this as a sextet confirms the product is the secondary amine.

| R | IRMOF-3 / % | by-products / % | **2** / % |
|---|---|---|---|
| Me (**2a**) | 51 | 0 | 49 |
| Et (**2b**) | 55 | 3 | 42 |
| Pr (**2c**) | 64 | 0 | 36 |
| $C_7H_{15}$ (**2d**) | 69 | 0 | 31 |

**Table 2.** Conversion of IRMOF-3 into the secondary amine-functionalised MOFs **2a-d** at room temperature in THF-MeOH (15:1) after 3d.

improves the conversion to the secondary amine. As anticipated, MeOH was able to solubilise the boron-containing side-product and, in support of this, the $^{11}$B NMR spectrum of the digested product from the reaction carried out in THF-MeOH showed no trace of the signal at δ 22 ppm, nor any other signal. Another consequence of introducing MeOH is the suppression of the formation of the MOF by-products observed in its absence. These are reduced from a maximum of ~50% in THF to less than 5% in **2a-d** – indeed they are only detected at all in the case of **2b**. Although addition of MeOH is clearly beneficial, carrying out the reactions in pure MeOH leads to degradation of the crystals, so the use of a THF-MeOH solvent mix appears to be best compromise for this PSM process.

The degree of conversion at room temperature decreases with increasing chain length of the reagent. Similar results have been observed with the conversion of IRMOF-3 to amides and ureas,[5, 7] largely as a consequence of the longer chains blocking access to unfunctionalised pores. In previously reported PSM processes, the degree of conversion was enhanced by carrying out the reactions at elevated temperatures. In order to assess whether this is also the case for the tandem condensation-reduction process described herein, the reactions with RCHO (R = Et, Pr, $C_7H_{15}$) were carried out at 50 °C. The reaction with MeCHO was not carried out at this temperature due to its volatility. The products were isolated and analysed in the same manner as the reactions at room temperature, and the results are summarised in Table 3. Again, powder X-ray diffraction confirmed that the MOF networks are unaltered during the PSM process. In all cases, carrying out the reaction at higher temperature increases the conversion to the desired secondary amine product. The increase is less than expected for **2b** due to the volatility of EtCHO.

| R | THF (RT) | THF-MeOH (RT) | THF-MeOH (50 °C) |
|---|---|---|---|
| Me (**2a**) | 33 | 49 | – |
| Et (**2b**) | 5 | 42 | 52 |
| Pr (**2c**) | 8 | 36 | 67 |
| $C_7H_{15}$ (**2d**) | 9 | 31 | 41 |

**Table 3.** Percentage conversion of IRMOF-3 into the secondary amine-functionalised MOFs **2a-d** after 3d as a function of solvent and temperature.

## Conclusions

We have demonstrated that a condensation-reduction tandem post-synthetic modification protocol can be used to convert the primary amine in IRMOF-3 into a range of secondary amine-containing MOFs with up to 67% completion. The presence of MeOH in the solvent mix is important in removing boron-containing side-products from the pores and minimising the formation of MOF by-products.

This tandem modification process is significant, as the resultant secondary amine groups are chemically more stable than the imine groups that are formed in the initial condensation process. Current work is looking to further optimise the reaction conditions for the tandem process and extend it to other $NH_2$-functionalised MOFs. In addition, we are working to include additional functionalities into the modified MOFs by using aldehydes that contain a second functional group.

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## Notes and references

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‡ A typical PSM procedure: Crystals of IRMOF-3 (0.100 g) were treeated with four equivalents of RCHO in THF or THF-MeOH (15:1) for 24 h. Four equivalents of $NaBH_3CN$ were then added to the reaction mixture, which was left for a further 48 h. The product was washed with THF or THF-MeOH.

1. C. Janiak and J. K. Vieth, *New J. Chem.*, 2010, **34**, 2366.
2. A. U. Czaja, N. Trukhan and U. Müller, *Chem. Soc. Rev.*, 2009, **38**, 1284; L. J. Murray, M. Dinca and J. R. Long, *Chem. Soc. Rev.*, 2009, **38**, 1294; Y.-S. Bae and R. Q. Snurr, *Angew. Chem. Int. Ed.*, 2011, **50**, 11586; A. Corma, H. García and F. X. Llabrés i Xamena, *Chem. Rev.*, 2010, **110**, 4606.
3. S. M. Cohen, *Chem. Rev.*, 2012, **112**, 970.
4. A. D. Burrows, C. G. Frost, M. F. Mahon and C. Richardson, *Angew. Chem. Int. Ed.*, 2008, **47**, 8482.
5. K. K. Tanabe, Z. Wang and S. M. Cohen, *J. Am. Chem. Soc.*, 2008, **130**, 8508.
6. T. Ahnfeldt, D. Gunzelmann, T. Loiseau, D. Hirsemann, J. Senker, G. Férey and N. Stock, *Inorg. Chem.*, 2009, **48**, 3057.
7. E. Dugan, Z. Wang, M. Okamura, A. Medina and S. M. Cohen, *Chem. Commun.*, 2008, 3366.
8. M. Savonnet, D. Bazer-Bachi, N. Bats, J. Perez-Pellitero, E. Jeanneau, V. Lecocq, C. Pinel and D. Farrusseng, *J. Am. Chem. Soc.*, 2010, **132**, 4518.
9. Z. Wang and S. M. Cohen, *Angew. Chem. Int. Ed.*, 2008, **47**, 4699.
10. W. Morris, C. J. Doonan, H. Furukawa, R. Banerjee and O. M. Yaghi, *J. Am. Chem. Soc.*, 2008, **130**, 12626; J. A. Rood, B. C. Noll and K. W. Henderson, *Main Group Chem.*, 2009, **8**, 237; J. Canivet, S. Aguado, C. Daniel and D. Farrusseng, *ChemCatChem*, 2011, **3**, 675.
11. M. J. Ingleson, J. Perez Barrio, J.-B. Guilbaud, Y. Z. Khimyak and M. J. Rosseinsky, *Chem. Commun.*, 2008, 2680; C. J. Doonan, W. Morris, H. Furukawa and O. M. Yaghi, *J. Am. Chem. Soc.*, 2009, **131**, 9492; S. Bhattacharjee, D. A. Yang and W.-S. Ahn, *Chem. Commun.*, 2011, **47**, 3637.
12. W. Morris, C. J. Doonan and O. M. Yaghi, *Inorg. Chem.*, 2011, **50**, 6853.
13. S. M. Cohen, *Chem. Sci.*, 2010, **1**, 32.
14. D. Britt, C. Lee, F. J. Uribe-Romo, H. Furukawa and O. M. Yaghi, *Inorg. Chem.*, 2010, **49**, 6387.
15. K. M. L. Taylor-Pashow, J. Della Rocca, Z. Xie, S. Tran and W. Lin, *J. Am. Chem. Soc.*, 2009, **131**, 14261.
16. M. Eddaoudi, J. Kim, N. Rosi, D. Vodak, J. Wachter, M. O'Keeffe and O. M. Yaghi, *Science*, 2002, **295**, 469.
17. Z. Wang, K. K. Tanabe and S. M. Cohen, *Inorg. Chem.*, 2009, **48**, 296.
18. Z. Wang and S. M. Cohen, *J. Am. Chem. Soc.*, 2007, **129**, 12368.