Supplementary Information

Alternative Synthetic Methodology for Amide Formation in the Post-Synthetic Modification of Ti-MIL125-NH_2

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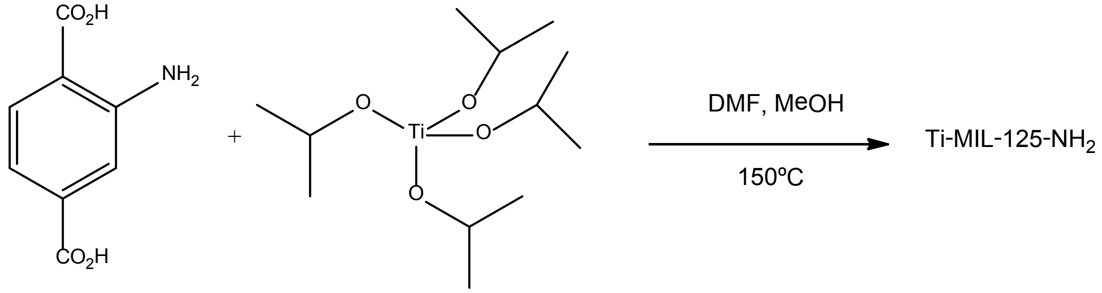
Ti-MIL-125-NH_2 ($Ti_8O_8(OH)_4[O_2C\text{-}C_6H_3(NH_2)\text{-}CO_2]_6$)

Adapted from previously published work.[1]



$Ti(O^iPr)_4$ (7.5 ml, 25 mmol) was added to 2-aminoterephthalic acid (7.5 g, 41 mmol) in DMF (50 ml) and methanol (25 ml) and the mixture heated in Parr apparatus under autogenous pressure at 150 °C for 16 hours. The light yellow powder was collected under suction, washed with DMF (2 x 10 ml), acetone (2 x 10 ml) and dried under air at room temperature. The solid was stirred in DMF overnight and then in methanol for 2 nights (methanol changed after 24 hours). The final product was collected under suction and dried *in vacuo* at 150 °C for 8 hours to give a light orange solid (3.8 g, 7 %).

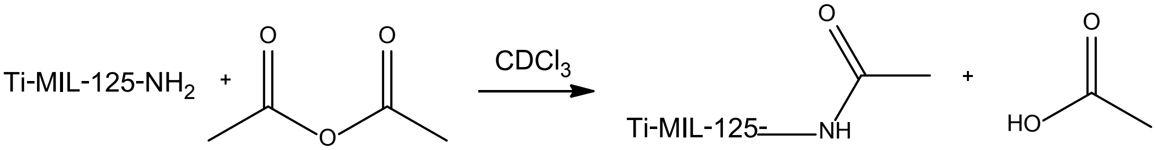
The structural solution was performed by starting with the coordinates for the known MIL125 structure. NH_2 groups were added, which were set as a disordered group with equal occupancy for all four positions on the terephthalate rings. Effectively they can be found in all four positions on the aromatic rings as has been seen in similar PCP structures of 2-amino-terephthalate. Included water molecules were placed in reasonable positions, many of which were special positions. Reitveld refinement was then performed utilising the CIF produced from this model structure. Atomistic positions were left unrefined. Any attempts to refine them resulted in collapse of the structure. Convergence occurred when refinement of the unit cell parameters, peak fitting, background fitting and displacement parameters was performed.

Post-Synthetic Modifications

Note: The PCPs used for PSM were activated before reaction by heating *in vacuo*.
NMR spectra give a mixture of modified/unmodified organic groups – the ^{1}H NMR peaks can be assigned by considering the peak integrations.

Acetic Anhydride PSM

Adapted from previously published work.[2]



For testing of solution (see S3):
A solution of acetic anhydride (0.1 ml, 1 mmol) in $CDCl_3$ (5 ml) was added equally to five separate vials containing activated Ti-MIL-125-NH_2 (28 mg, 0.1 mmol relative to NH_2). The vials were swirled then left to react for a given time period (1, 2, 3, 4, 53 hours). The solution was removed and analysed by ^{1}H NMR while the solid was washed with DCM (3 x 1 ml) and left to soak in DCM for 3 days (DCM changed every 24 hours). The solid was then dried *in vacuo* to yield the orange modified PCP.

For testing of solid:
A solution of acetic anhydride (2 ml, 21 mmol) in $CHCl_3$ (15 ml) was added to activated Ti-MIL-125-NH_2 (276 mg, 1 mmol relative to NH_2) and the solution stirred for 60 hours. The solid was collected under suction, washed with DCM (3 x 10 ml) and acetone (10 ml) then stirred in DCM (5 ml) overnight. The washing procedure was then repeated after which the orange solid product was dried at 150 °C *in vacuo* (215 mg).
^{1}H NMR: (400 MHz, d_6-DMSO/DCl/D_2O), δ/ppm:
Modified: 8.71 (s, 1H, Ar-H); 7.88 (d, 1H, J 8.0 Hz, Ar-H); 7.53 (d, 1H, 8.0 Hz, Ar-H); 1.99 (s, 3H, Me)
Unmodified: 7.95 (d, 1H, J 8.0 Hz, Ar-H); 7.94 (s, 1H, Ar-H); 7.73 (d, 1H, Ar-H)

IR (cm^{-1}): 3307; 1686; 1537; 1509; 1422; 1377; 1297; 1270; 1044; 771

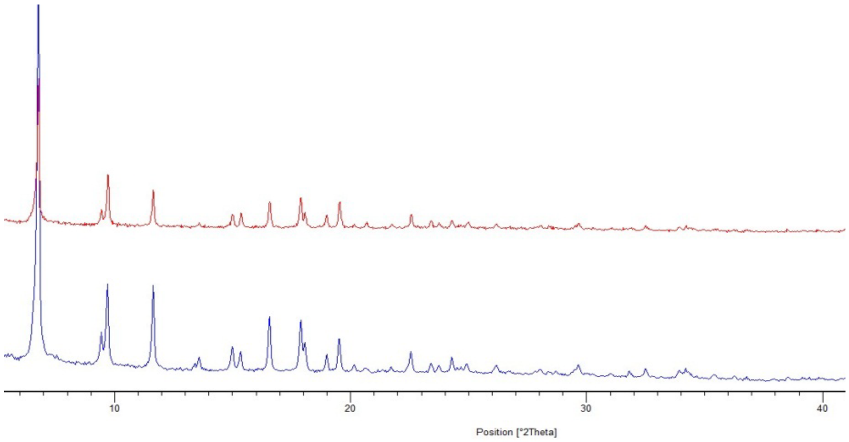


Figure S1. PXRD pattern of the modified Ti-MIL-125-NH_2 (red, top) is unchanged compared with that of the unmodified PCP (blue, bottom).

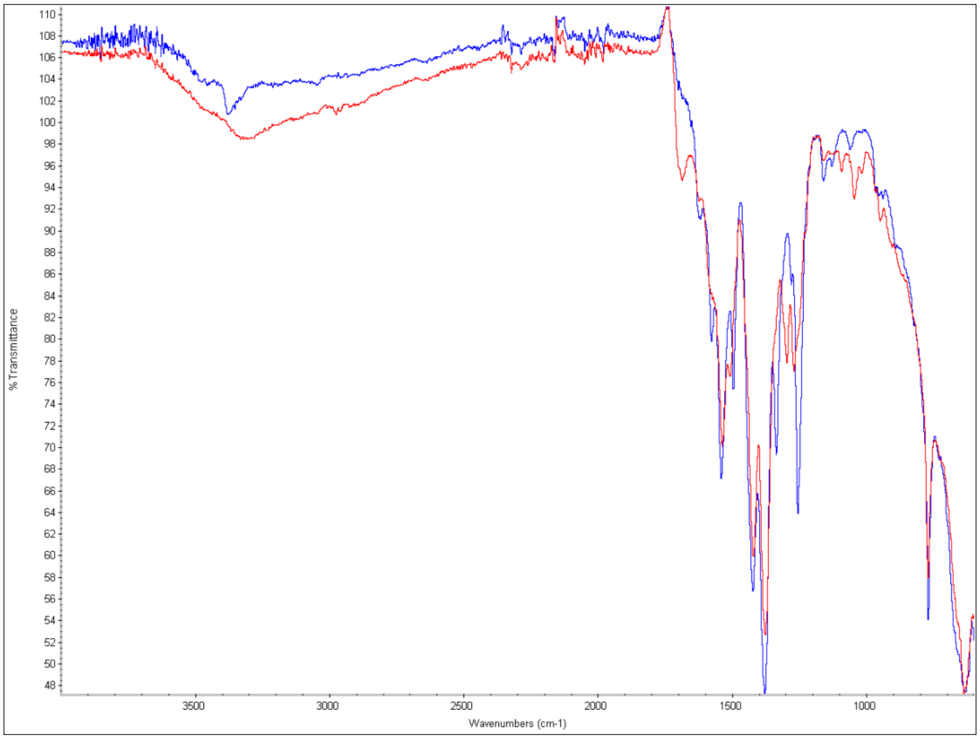


Figure S2. FT-IR of the acetic anhydride modified PCP (red) compared with the unmodified Ti-MIL-125-NH_2 (blue) which shows the appearance of a new peak at 1686 cm^{-1} due to the amide carbonyl stretch.

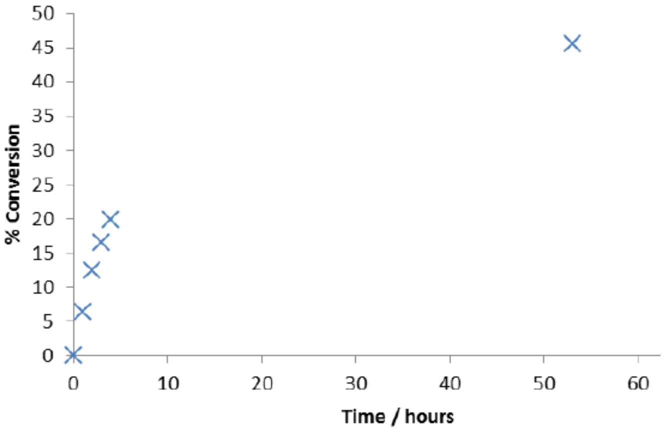


Figure S3. Graph showing the conversion of amine groups in Ti-MIL-125-NH$_2$ to the amide by reaction with acetic anhydride in CDCl$_3$. ^{1}H NMR analysis of the resulting solution allowed the comparison of the relative amounts of acetic anhydride starting material and acetic acid by-product to give a measure of the extent of reaction.

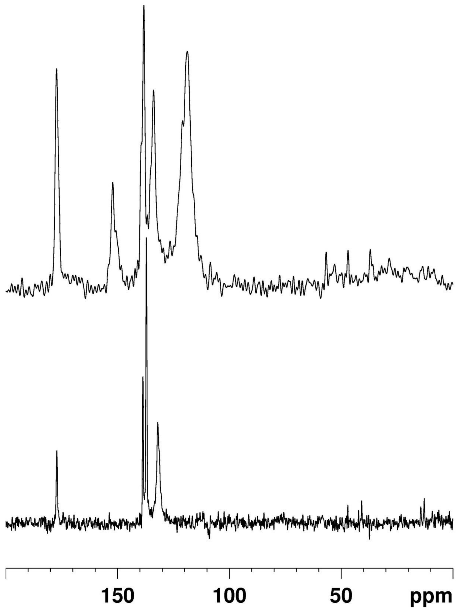
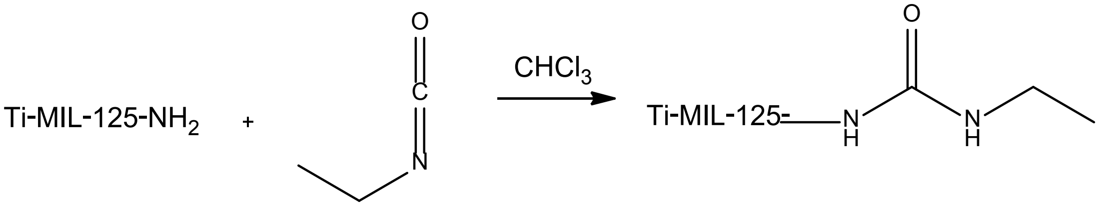


Figure S4. ^{13}C Solid state NMR comparing MIL125-NH$_2$ (Top) with MIL125 (Bottom).

Ethyl Isocyanate PSM



Ethyl isocyanate (130 µl, 1.6 mmol) was added to activated Ti-MIL-125-NH$_2$ (96 mg, 0.35 mmol relative to NH$_2$) in CHCl$_3$ (2 ml) and the mixture stirred for 48 hours at 50

°C. The liquid was filtered off and the solid washed with $CHCl_3$ (2 x 2 ml) and acetone (2 ml). The solid was then stirred in $CHCl_3$ for 12 hours and the washing procedure repeated to give, after drying *in vacuo*, an orange solid product (71 mg).

^{1}H NMR: (400 MHz, d_6-DMSO/DCl/D_2O), δ/ppm:
Mixture of both modified and unmodified: 7.95 (m, Ar-H); 7.84 (dd, J=8.1, 1.6 Hz, Ar-H); 2.62 (q, '2H', 7.3 Hz, CH_2); 0.95 (t, '3H', 7.3 Hz, Me)
IR (cm^{-1}): 3358; 1702; 1540; 1496; 1425; 1380; 1339; 1257; 1157; 768

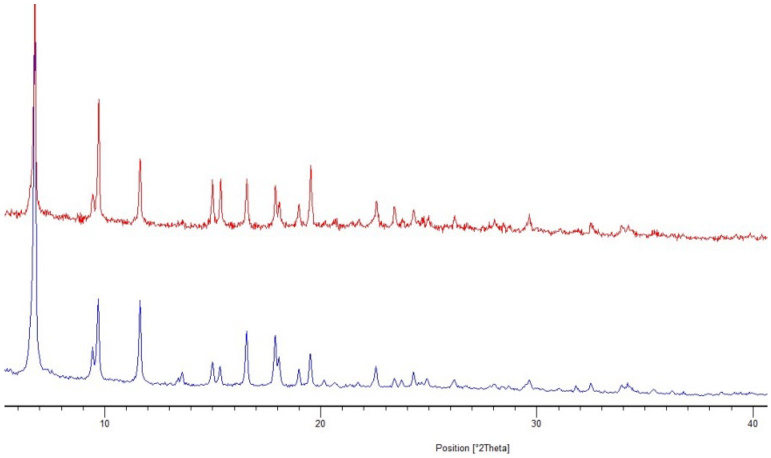
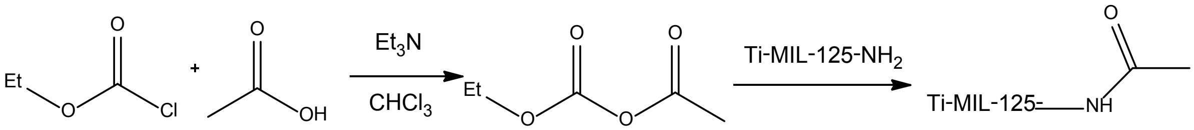


Figure S5. PXRD patterns of pristine MIL125-NH_2 (Blue, bottom) compared to the PSM with ethyl isocyanate MIL125-NH_2.

Activated Acetic Acid PSM

Adapted from previously published work.[3]

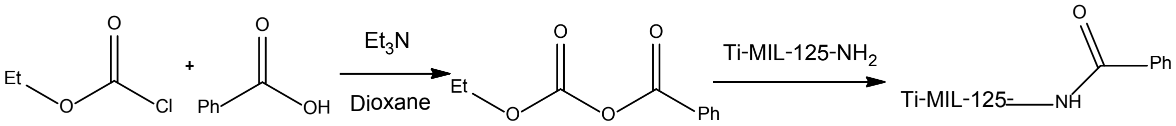


Ethyl chloroformate (95 µl, 1 mmol) in $CHCl_3$ (15 ml) was added dropwise to a stirred, cooled (0 °C) solution of triethylamine (154 µl, 1.1 mmol) and acetic acid (57 µl, 1 mmol) in $CHCl_3$ (35 ml). The mixture was stirred at room temperature for 30 minutes after which activated Ti-MIL-125-NH_2 (276 mg, 1 mmol based on NH_2) was added and the solution stirred for a further 72 hours. The solid was collected under suction, washed with water (2 x 10 ml) and acetone (10 ml) then stirred in water (30 ml) overnight. The washing procedure was repeated and the resulting orange solid was then dried under high vacuum (261 mg).

^{1}H NMR: (400 MHz, d_6-DMSO/DCl/D_2O), δ/ppm:
Modified: 8.72 (s, 1H, Ar-H); 7.89 (d, 1H, J 8.0 Hz, Ar-H); 7.54 (d, 1H, 8.0 Hz, Ar-H); 2.00 (s, 3H, Me)
Unmodified: 7.96 (d, 1H, J 8.0 Hz, Ar-H); 7.94 (s, 1H, Ar-H); 7.74 (d, 1H, Ar-H)
IR (cm^{-1}): 3327; 1685; 1537; 1422; 1379; 1298; 1258; 1158; 769

Activated Benzoic Acid PSM

Adapted from previously published work.[3]



Ethyl chloroformate (33 µl, 0.35 mmol) in dioxane (10 ml) was added dropwise to a stirred, cooled (0 °C) solution of triethylamine (56 µl, 0.4 mmol) and benzoic acid (43 mg, 0.35 mml) in dioxane (30 ml). The mixture was stirred at room temperature for 30 minutes after which activated Ti-MIL-125-NH_2 (96 mg, 0.35 mmol based on NH_2) was added and the solution stirred for a further 72 hours.

The solid was collected under suction, washed with water (2 x 10 ml) and acetone (10 ml) then stirred in water (30 ml) overnight. The washing procedure was repeated and the resulting orange solid was then dried under high vacuum. (37 mg)

IR (cm^{-1}): 3327; 1701; 1624; 1577; 1540; 1496; 1425; 1381; 1339; 1257; 1154; 769

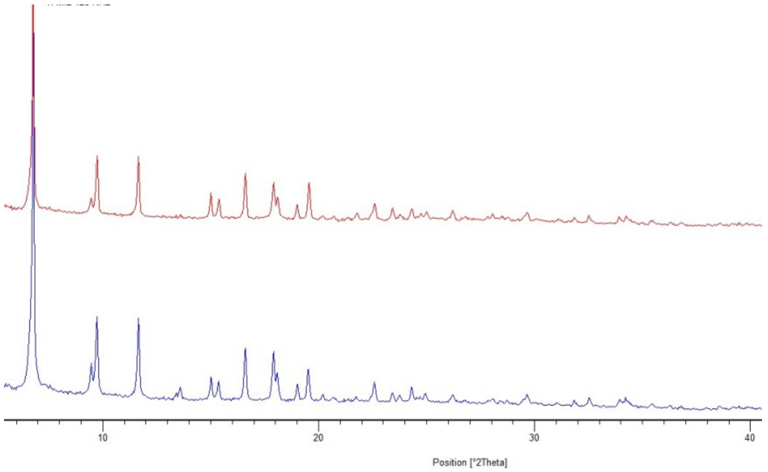
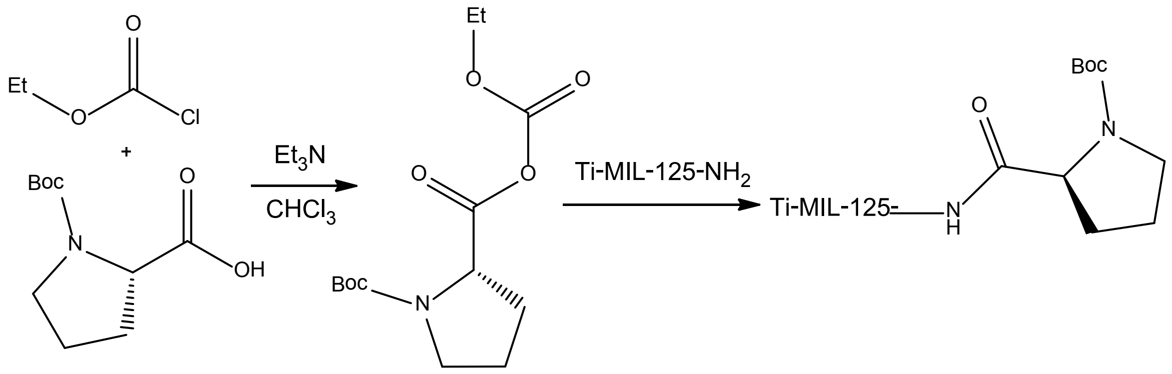


Figure S6. PXRD patterns of pristine MIL125-NH_2 (Blue, bottom) compared to the PSM with benzoic acid MIL125-NH_2.

Activated Boc-L-Proline PSM

Adapted from previously published work.[3]



Ethyl chloroformate (95 µl, 1 mmol) in $CHCl_3$ (15 ml) was added dropwise to a stirred, cooled (0 °C) solution of triethylamine (154 µl, 1.1 mmol) and Boc-L-Proline (215 mg, 1 mmol) in $CHCl_3$ (35 ml). The mixture was stirred at room temperature for 30 minutes after which activated Ti-MIL-125-NH_2 (276 mg, 1 mmol based on NH_2) was added and the solution stirred for a further 72 hours. The solid was collected under suction, washed with water (2 x 10 ml) and acetone (10 ml) then stirred in water (30 ml) overnight. The washing procedure was repeated and the resulting orange solid was then dried under high vacuum (235 mg).

IR (cm^{-1}): 3361; 1701; 1624; 1574; 1537; 1496; 1424; 1380; 1339; 1256; 1159; 1116; 769

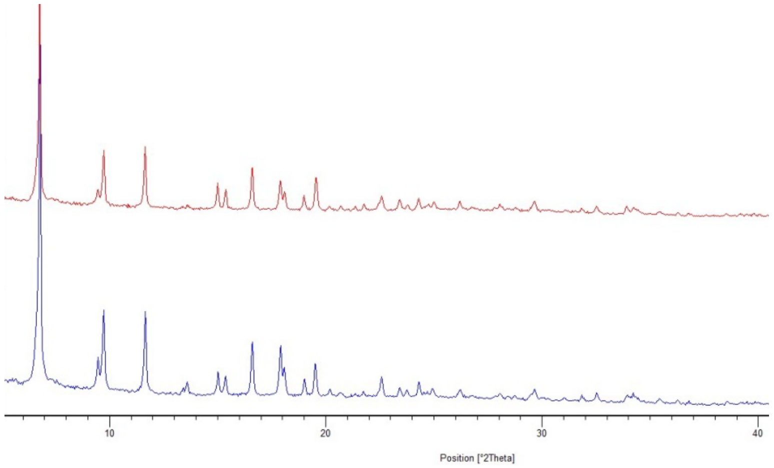
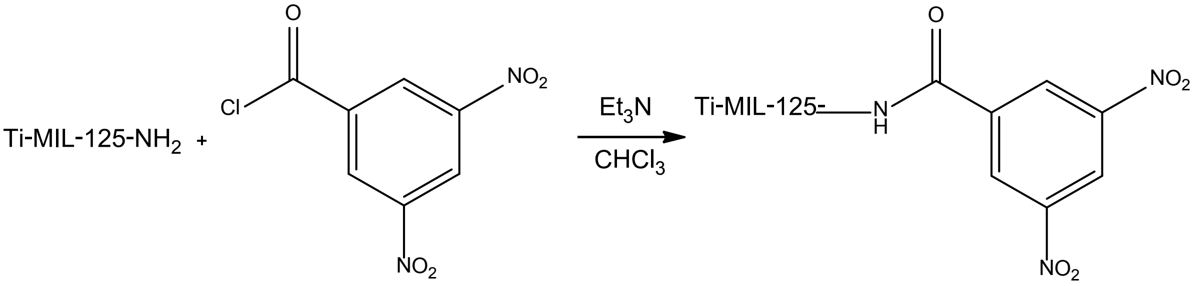


Figure S7. PXRD patterns of pristine MIL125-NH_2 (Blue, bottom) compared to the PSM with Boc-L-Proline MIL125-NH_2.

3,5-Dinitrobenzoyl Chloride PSM



A solution of 3,5-dinitrobenzoyl chloride (81 mg, 0.35 mmol) and triethylamine (0.5 ml, 3.6 mmol) in THF (2 ml) was added to Ti-MIL-125-NH_2 (96 mg, 0.35 mmol relative to NH_2) in THF (3 ml) and the mixture was stirred for 12 hours. The resulting solid was washed with THF (3 x 3 ml) and stirred in THF (5 ml) overnight. The solution was removed then the solid was washed with THF (2 x 1 ml) and dried *in vacuo* at 100 °C to yield an orange powder (58 mg).

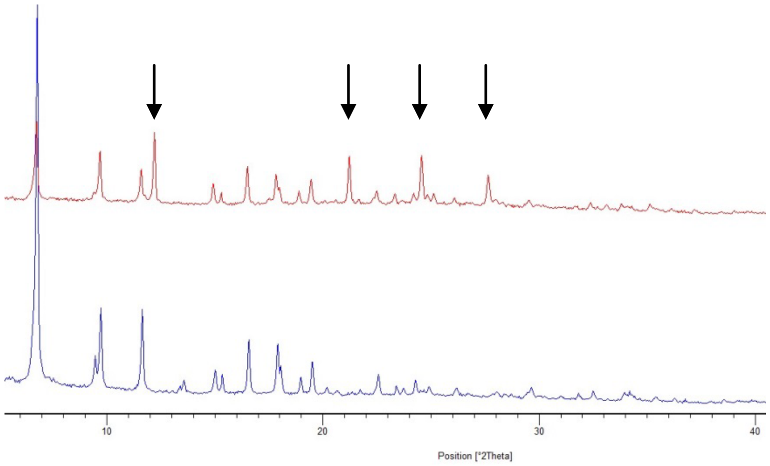


Figure S8. PXRD showing the unmodified Ti-MIL-125-NH_2 (blue, bottom) compared with the reacted PCP (red, top). The introduction of new peaks indicates the production of a new crystalline material we is produced from the HCl digestion of the MIL material. The HCl is produced from the reaction of the acid chloride with the amino functional groups.

Gas sorption

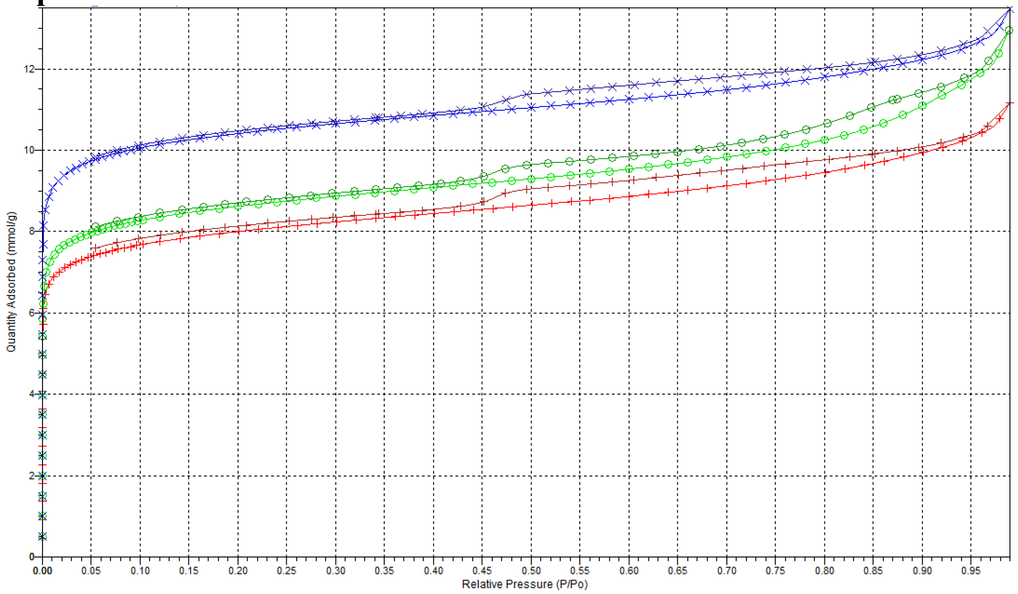


Figure S9. Gas isotherms of the pristine MIL125-NH$_2$ (Blue, top) and the PSM modified with acetic anhydride (Red, bottom) and asymmetric anhydride (Green, middle).

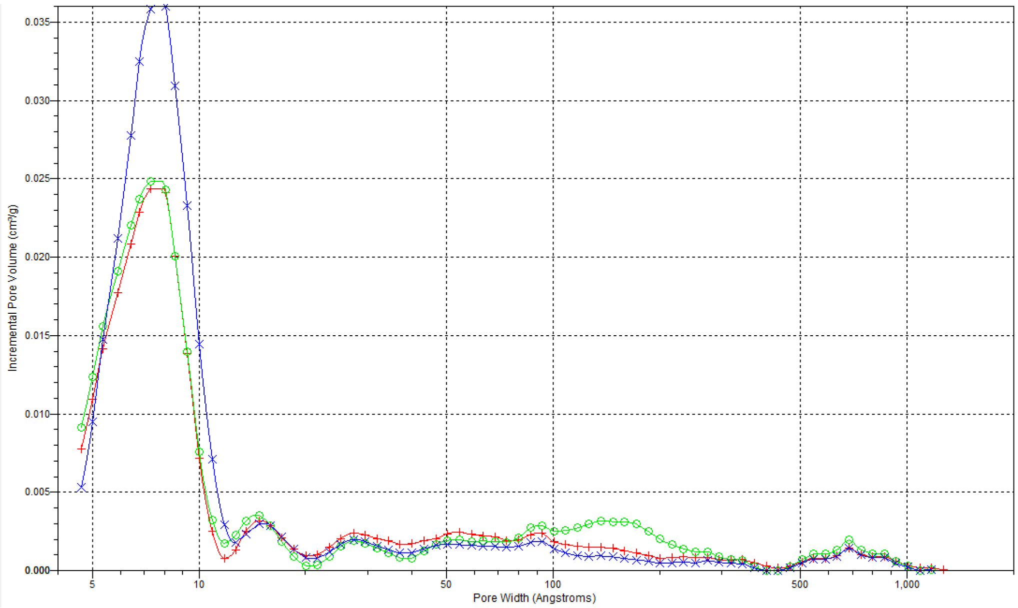


Figure S10. Incremental Pore Volume versus Pore Width of the pristine MIL125-NH$_2$ (Blue, top) and the PSM modified with acetic anhydride (Red, bottom) and asymmetric anhydride (Green, middle).

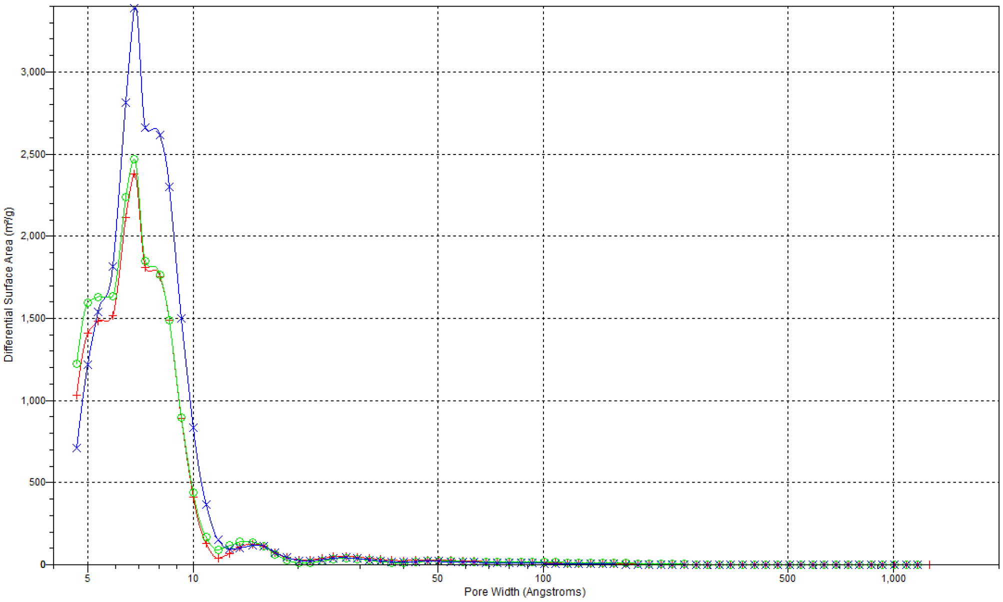


Figure S11. Differential Surface Area versus Pore Width of the pristine MIL125-NH_2 (Blue, top) and the PSM modified with acetic anhydride (Red, bottom) and asymmetric anhydride (Green, middle).

UiO-66-NH_2

Adapted from previously published work.[4]

2-aminoterephthalic acid (127 mg, 0.7 mmol) and $ZrCl_4$ (163 mg, 0.7 mmol) were placed in DMF (8 ml) and heated in Parr apparatus at 120 °C for 24 hours. The solid was collected under suction and heated at 100 °C for 1 - 2 hours. The solid was then washed with methanol (3 x 5 ml) and soaked in methanol for 72 hours. The liquid was decanted and the solid heated at 150 °C for 12 hours then dried under high vacuum to give a light yellow powder (122 mg, 63 %).

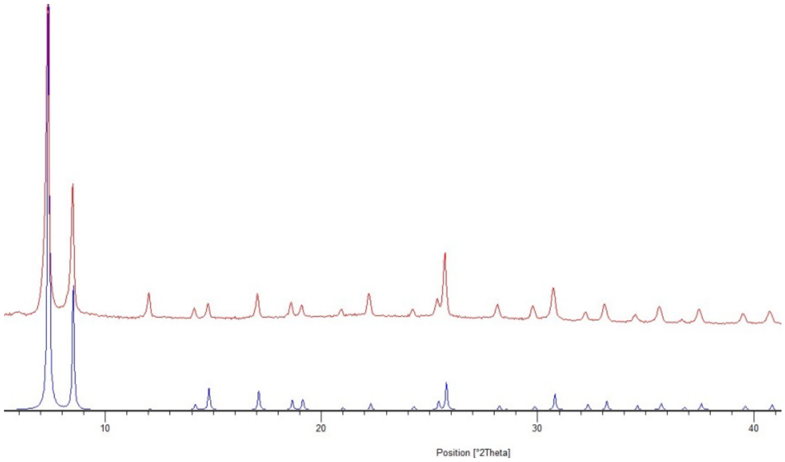


Figure S12. PXRD of UiO-66-NH_2 (red, top) compared with the simulated pattern for UiO-66 (blue, bottom).

MS of digested MIL materials

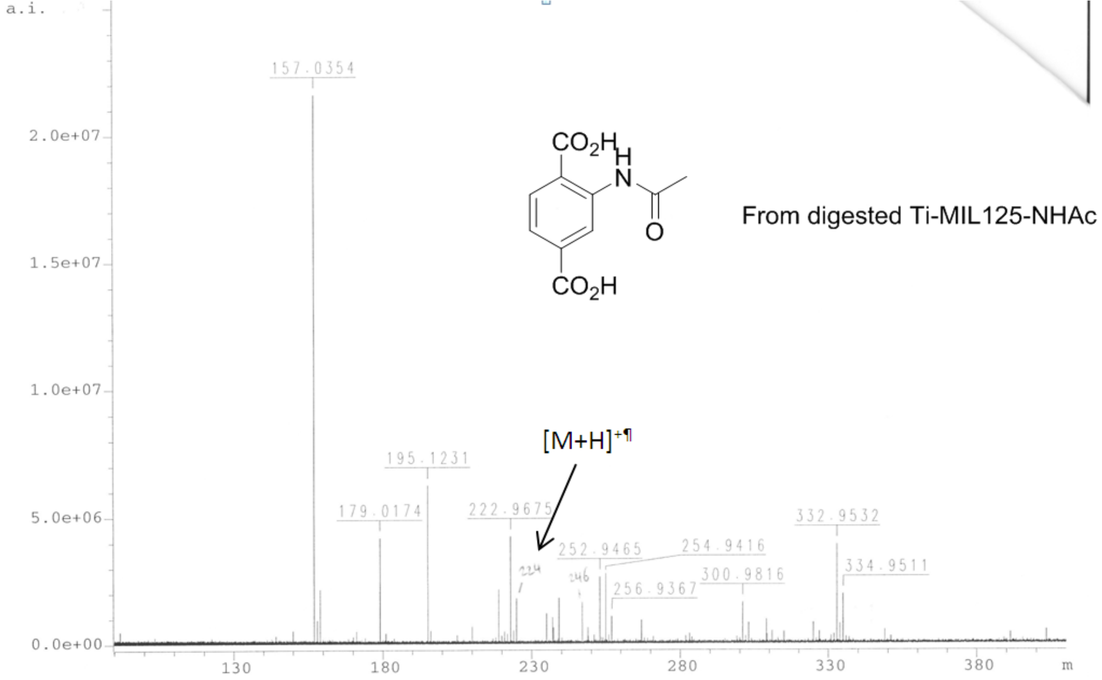


Figure S13. ESI$^+$ MS of digested MIL125-NHCOCH$_3$ from symmetric anhydride PSM. 224 m/z is M+H$^+$ and 246 m/z is M+Na$^+$.

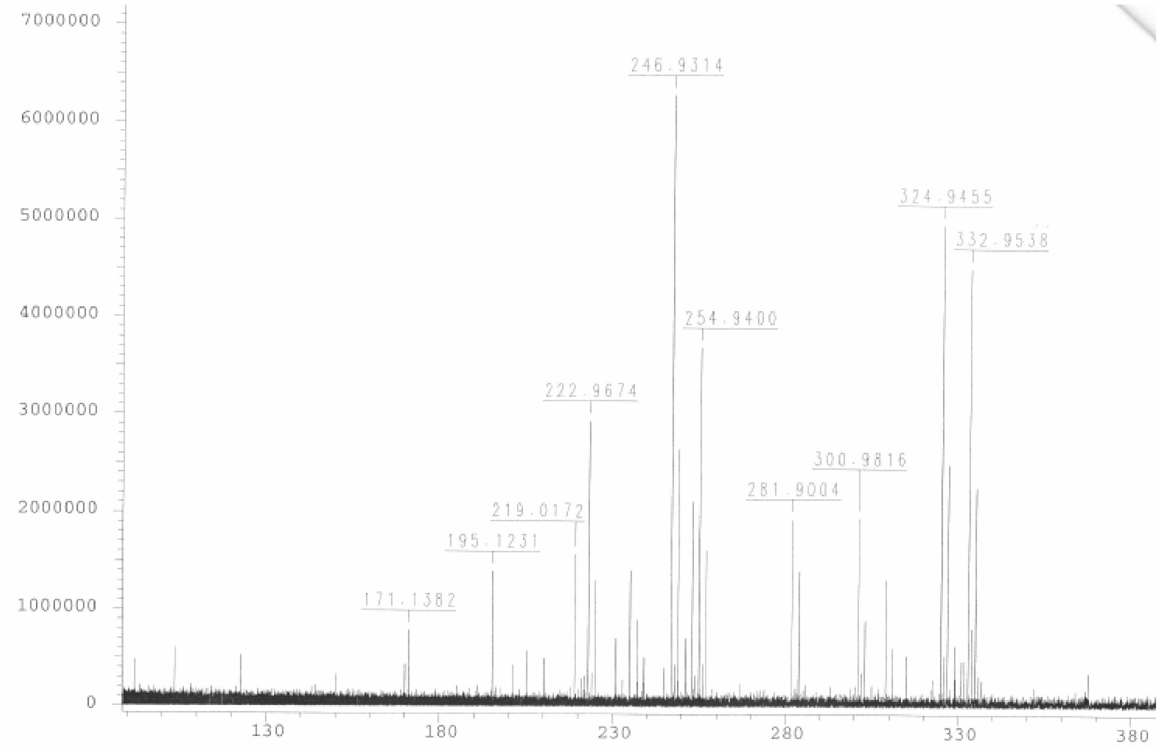


Figure S14. ESI$^+$ MS of digested MIL125-NHCOCH$_3$ from asymmetric anhydride PSM. 224 m/z is M+H$^+$ and 246 m/z is M+Na$^+$.

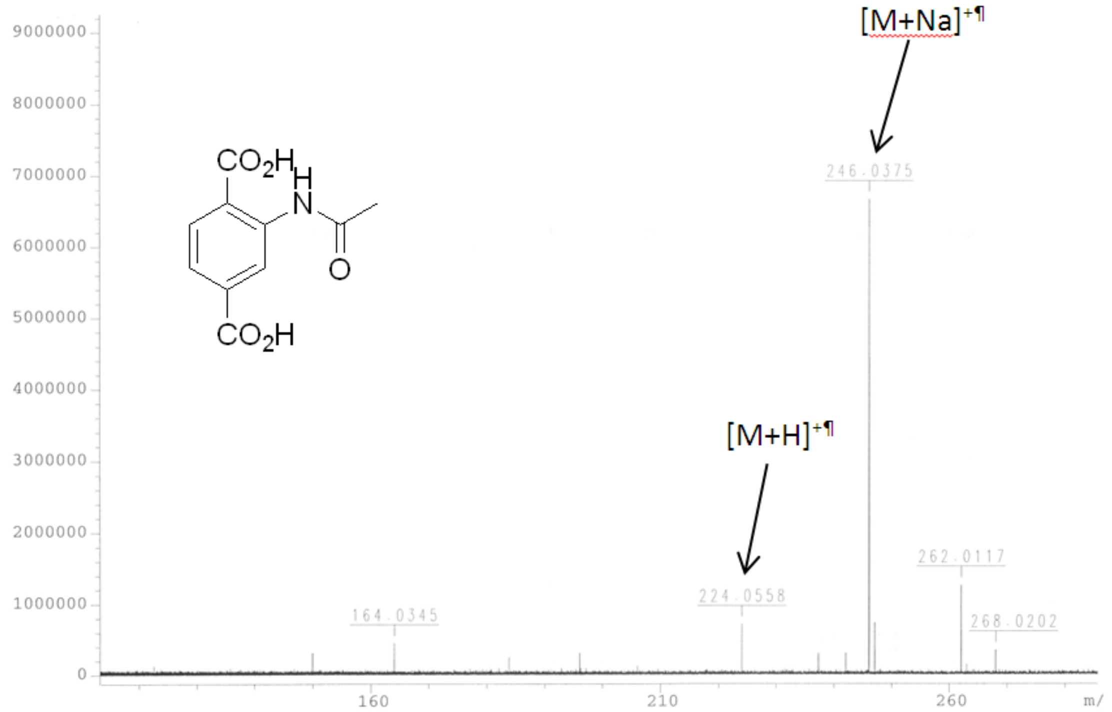


Figure S15. ESI$^+$ MS of pure terephthalic acid-NHCOCH$_3$ for comparison.

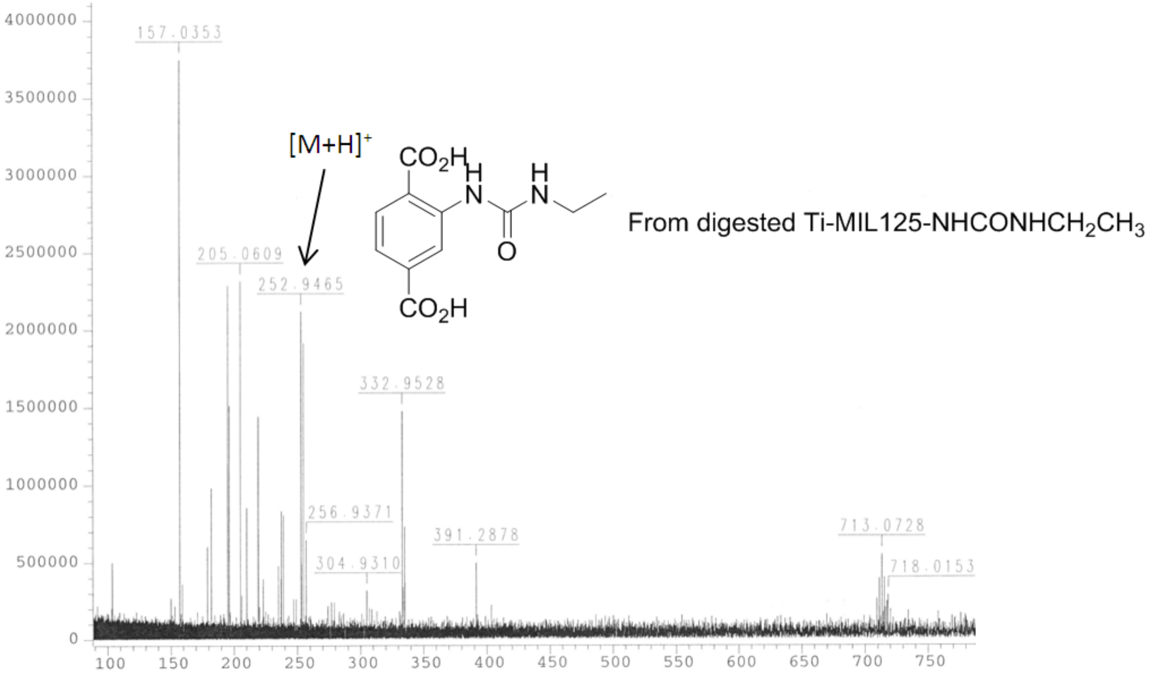


Figure S16. ESI$^+$ MS of digested PSM ethyl isocyanate MIL125, MIL125-NHCONHEt.

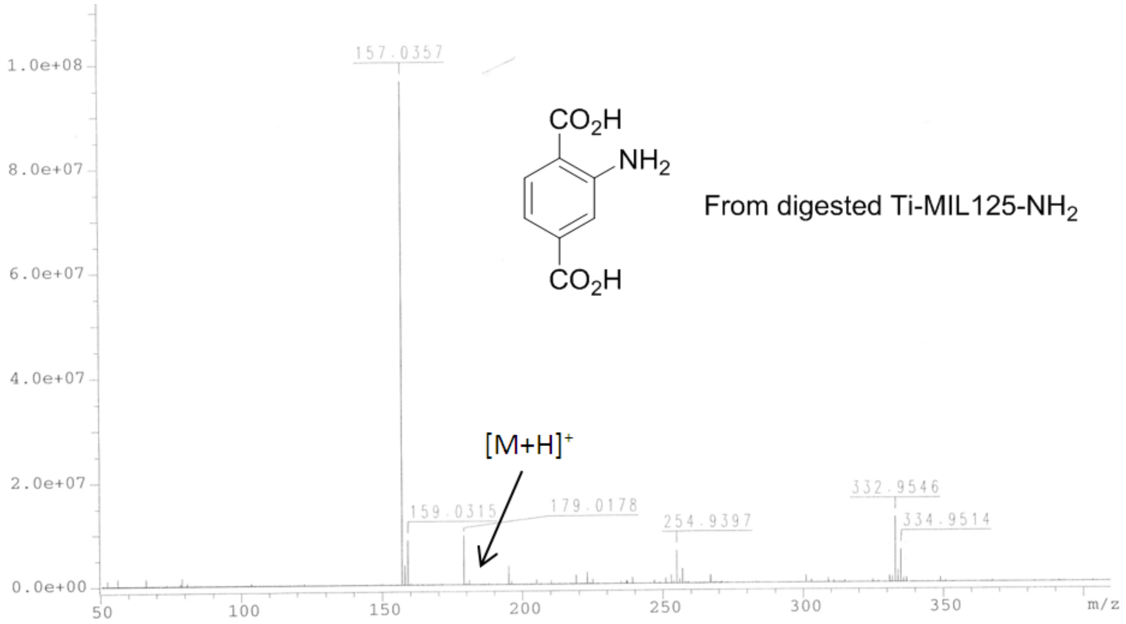


Figure S17. ESI$^+$ MS of digested Ti-MIL125-NH$_2$.

Equipment/Experimental protocols

Digestion experiments

Solution NMRs require the PCP/MOF to be digested in order to allow the organic groups to be dissolved. For Ti-MIL125-NH$_2$ and UiO-66-NH$_2$ concentrated HCl is a strong enough acid to break up the PCP for this purpose. The usual procedure was to add 3-5 drops of DCl and 600 µl d$_6$-DMSO to about 10 mg solid. Sonication, if required, was used to aid solubilisation. [This dissolution technique was also used for mass spectrometry measurements.]

Powder X-Ray Diffraction (PXRD) patterns were obtained on a flat bracket using an X'Pert MPD Powder X-Ray Diffractometer and analysed using the PANalytical X'Pert Highscore program.

Fourier Transform Infrared (FT-IR) spectra were obtained using solid samples on a Thermo Nicolet Nexus FT-IR device with the Smart Golden Gate ATR attachment and analysed using the program OMNIC.

Solution State ^{1}H and ^{13}C Nuclear Magnetic Resonance (NMR) spectra were obtained at 400 MHz for ^{1}H and 100 MHz for ^{13}C using a Bruker Avance III 400 QNP Ultrashield spectrometer.

Solid State ^{13}C NMR spectra were obtained on a Bruker Avance 400 NMR spectrometer with a frequency of 100 MHz. The magic angle spinning frequency was 12.5 kHz with a standard cross polarization of 2.5 ms used for sensitivity enhancement and a recycle time of 2 s. Chemical shifts were referenced to the methylene signal of a glycine sample at 43.1 ppm.

Mass Spectrometry (MS) was run on a Thermo Scientific Orbitrap or a Bruker BioApex II FTICR.

Thermogravimetric Analysis (TGA) was performed using 100 µl aluminium pans with a heating rate of 10 °C min^{-1} on a Mettler Toledo TGA device. The data were analysed using the Mettler STARe Basic software.

Elemental Analysis was run on an Exeter analytical 440 elemental analyser.

Rietveld Analysis was run on Topas Academic version 4.1, Alan Coelho.

Crystal Structure Images, Structural Construction and Visualisation was performed using the crystallographic software Xseed.[5]

References.

1. **Vermoortele, F., et al.** 2011, *J. Am. Chem. Soc.*, Vol. 133 (46), pp. 18526–18529.
2. **Tanabe, K.K., Wang, Z and Cohen, S.M.** 2008, *J. Am. Chem. Soc.*, Vol. 130, pp. 8508-8517.
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4. **Garibay, S.J. and Cohen, S.M.** 2010, *Chem Commun*, Vol. 46 (41), pp. 7700-7702.
5. **Barbour, L. J.**, 2001, *J. Supramol. Chem.*, Vol. 1, 189.