

Video Article

Synthesis and Characterization of Functionalized Metal-organic Frameworks

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Abstract

Metal-organic frameworks have attracted extraordinary amounts of research attention, as they are attractive candidates for numerous industrial and technological applications. Their signature property is their ultrahigh porosity, which however imparts a series of challenges when it comes to both constructing them and working with them. Securing desired MOF chemical and physical functionality by linker/node assembly into a highly porous framework of choice can pose difficulties, as less porous and more thermodynamically stable congeners (e.g., other crystalline polymorphs, catenated analogues) are often preferentially obtained by conventional synthesis methods. Once the desired product is obtained, its characterization often requires specialized techniques that address complications potentially arising from, for example, guest-molecule loss or preferential orientation of microcrystallites. Finally, accessing the large voids inside the MOFs for use in applications that involve gases can be problematic, as frameworks may be subject to collapse during removal of solvent molecules (remnants of solvothermal synthesis). In this paper, we describe synthesis and characterization methods routinely utilized in our lab either to solve or circumvent these issues. The methods include solvent-assisted linker exchange, powder X-ray diffraction in capillaries, and materials activation (cavity evacuation) by supercritical CO₂ drying. Finally, we provide a protocol for determining a suitable pressure region for applying the Brunauer-Emmett-Teller analysis to nitrogen isotherms, so as to estimate surface area of MOFs with good accuracy.

Video Link

The video component of this article can be found at <https://www.jove.com/video/52094/>

Introduction

Metal-organic frameworks (MOFs) are a class of crystalline coordination polymers consisting of metal-based nodes (e.g., Zn²⁺, Zn₄O⁶⁺, Zr₆O₄(OH)₄¹²⁺, Cr₃(H₂O)₂OF⁶⁺, Zn₂(COO)₄) connected by organic linkers (e.g., di-, tri-, tetra- and hexacarboxylates, imidazolates¹, dipyrityls; see **Figure 1**).² Their highly ordered (and thus amenable to high levels of characterization) structures, combined with their exceptional surface areas (reaching 7,000 m²/g)³ endow them with the potential as attractive candidates for a slew of applications, ranging from hydrogen storage⁴ and carbon capture^{5,6} to catalysis,^{7,8} sensing^{9,10} and light harvesting.¹¹ Not surprisingly, MOFs have elicited a great amount of interest in the science and materials engineering communities; the number of publications on MOFs in peer-reviewed journals has been increasing exponentially over the past decade, with 1,000-1,500 articles currently being published per year.

The synthesis of MOFs with desirable properties, however, poses a series of challenges. Their principal point of attraction, namely their exceptional porosity, in fact may present, for specific MOFs, one of the greatest obstacles towards their successful development. The large empty space present within the frameworks of these materials detracts from their thermodynamic stability; as a result, when MOFs are synthesized *de novo* (i.e., by solvothermally reacting the metal precursors and organic linkers in one step), their constituent building blocks often tend to assemble into denser, less-porous (and less desirable for some applications such as gas storage) analogues.¹² After the procedure to reproducibly obtain the framework of desirable topology has been developed, the MOF needs to be treated in order to enable its application in processes that require gas sorption. Since MOFs are synthesized in a solution, the cages and channels of the newly grown MOF crystals are typically full of the high-boiling solvent used as the reaction medium; the removal of the solvent without inducing the collapse of the framework under the capillary forces requires a series of specialized procedures known as "MOF activation".¹³ Finally, to ensure the purity of the end product and to enable conclusive studies of fundamental properties, MOFs need to be rigorously characterized upon their synthesis. Given the fact that MOFs are coordination polymers, which are highly insoluble in conventional solvents, this process often involves several techniques developed especially for this class of materials. Many of these techniques rely on X-ray diffraction (XRD), which is uniquely suited to provide high-level characterization of these crystalline materials.

Typically, MOF synthesis in the so-called *de novo* fashion employs one-pot solvothermal reactions between the metal precursors (inorganic salts) and the organic linkers. This method suffers from multiple limitations, as there is little control over the arrangement of the MOF components into the framework, and the resulting product does not always possess the desired topology. An easy to implement approach that allows

circumventing the problems associated with the *de novo* MOF synthesis is solvent-assisted linker exchange (SALE, **Figure 2**).¹⁴⁻¹⁶ This method involves exposing easily obtainable MOF crystals to a concentrated solution of the desired linker, until the daughter linkers completely replace those of the parent. The reaction proceeds in a single crystal-to-single crystal fashion — that is, despite the replacement of the linkers within the framework, the material retains the topology of the original parent MOF. SALE essentially allows synthesis of MOFs with linker-topology combinations that are difficult to access *de novo*. So far, this method has been successfully implemented to overcome various synthetic MOF challenges, such as control over catenation,¹⁷ expansion of MOF cages,^{18,19} synthesis of high energy polymorphs²⁰, development of catalytically active materials^{20,21} and site-isolation to protect reactive reagents.²²

Freshly synthesized MOFs almost always have channels filled with the solvent used during their synthesis. This solvent needs to be removed from the frameworks in order to take advantage of their gas sorption properties. Conventionally, this is achieved by a) exchanging the solvent in the channels (usually a high boiling solvent like *N,N*-dimethylformamide, DMF) with a more volatile solvent like ethanol or dichloromethane by soaking the MOF crystals in the solvent of choice, b) heating the MOF crystals under vacuum for prolonged times to evacuate the solvent, or c) a combination of these two techniques. These activation methods are, however, not suitable for many of the high-surface thermodynamically fragile MOFs that may suffer from framework collapse under such harsh conditions. A technique that allows solvent removal from the cages of the MOF, while avoiding the onset of extensive framework collapse, is activation through supercritical CO₂ drying.²³ During this procedure, the solvent inside the MOF structure is replaced with liquid CO₂. The CO₂ is subsequently heated and pressurized past its supercritical point, and eventually allowed to evaporate from the framework. Since supercritical CO₂ does not possess capillary forces, this activation treatment is less forcing than conventional vacuum heating of MOFs, and has enabled access to most of the ultrahigh Brunauer-Emmett-Teller (BET) surface areas that have been published so far, including the MOF with the champion surface area.^{3,24,25}

In this paper, we describe the *de novo* synthesis of a representative easily accessible MOF that serves as a good template for SALE reactions — the pillared-paddlewheel framework **Br-YOMOF**.²⁶ Its long and relatively weakly bound *N,N'*-di-4-pyridyl naphthalenetetracarboxydiimide (**dpni**) pillars can be readily exchanged with *meso*-1,2-di(4-pyridyl)-1,2-ethanediol (**dped**) to produce an isostructural MOF **SALEM-5** (**Figure 2**).¹⁸ Furthermore, we outline the steps that need to be taken to activate **SALEM-5** by supercritical CO₂ drying and to successfully collect its N₂ isotherm and obtain its BET surface area. We also describe various techniques pertinent to MOF characterization, such as X-ray crystallography and ¹H NMR spectroscopy (NMR).

Protocol

1. Synthesis of the Parent MOF (Br-YOMOF)

1. Weigh out 50 mg Zn(NO₃)₂ × 6 H₂O (0.17 mmol), 37.8 mg **dpni** (0.09 mmol) and 64.5 mg 1,4-dibromo-2,3,5,6-tetrakis-(4-carboxyphenyl)benzene (**Br-tcpb**, 0.09 mmol). Combine all solid ingredients in a 4-dram vial.
2. Add 10 ml of DMF measured with a graduated cylinder to the vial with the solid ingredients. Then, using a 9" Pasteur pipet, add one drop (0.05 ml) of concentrated HCl (CAUTION! Corrosive to eyes, skin and mucous membrane. Handle with gloves.).
3. Tightly cap the vial and thoroughly mix the ingredients using an ultrasonication bath for ~15 min. Observe the contents of the vial as they form a suspension.
4. Place the vial in an oven at 80 °C for two days. On day 1, check the vial to ensure that its contents have completely dissolved, forming a yellow clear solution. On day 2, observe yellow tear-shaped crystals on the walls and the bottom of the vial. Following the formation of the crystals, remove the vial from the oven.
5. Allow the vial to cool to RT. Then use a spatula to gently push the crystals off the vial walls, so that they all collect on the floor of the vial. Let the vial stand for ~5 min to ensure that all the crystals have settled on the floor.
6. Using a 9" Pasteur pipet, gently remove the reaction solution from the vial, while avoiding sucking up the crystals into the pipet. Leave just enough solution so that the crystals are completely covered, to prevent the framework from drying out.
7. Add ~5 ml fresh DMF to the vial with the crystals. Soak the MOF crystals in fresh DMF for at least one day in order to remove the acidic reaction solution and any unreacted ingredients trapped in the MOF pores. For best results, periodically replace the DMF with fresh batches (~3 times over the course of the first hour, then every 6-12 hr).
8. Store the **Br-YOMOF** crystals in DMF at RT until further use.

2. Characterization by Powder X-ray Diffraction (PXRD)

1. Prepare a 0.7 mm diameter borosilicate glass capillary for the experiment by carefully cutting off the closed end so that the top 3 cm of the capillary (with the funnel top) remain.
2. Heat regular beeswax until it is melted and dip the narrow (cut) end of the capillary into the melted wax. Remove the capillary and let the wax solidify as a plug in the bottom of the capillary.
3. Support the capillary in a small amount of modeling clay.
4. Using a Pasteur pipet, draw up several milliliters of crystals in solution. Carefully transfer the crystals and solution to the capillary through the funnel opening. Use a paper towel or tissue to wick away excess solvent. Avoid spilling solvent or crystals on the outside of the capillary.
5. Allow the crystals to settle into a small plug (approximately 2-5 mm in length). Use a very small piece of modeling clay to seal the top (funnel) end of the capillary.
6. Remove any mounting devices from the goniometer head (brass pins, magnetic mounts, etc.) and place your capillary supported by modeling clay on top of the goniometer head.
7. Center the capillary in the X-ray beam to ensure that the plug of crystals does not precess as it rotates.
NOTE: The volume of crystalline material will exceed the beam size of most standard laboratory X-ray sources.
8. Using your diffractometer's software, prepare a series of 180° ϕ scans, in overlapping increments of 2 θ . For example, using a kappa-geometry diffractometer equipped with an Apex2 detector set at 150 mm (dx), we collect a series of 10-sec, 180° ϕ scans with the parameters as per **Table 1**.

- Once the frames have been collected, use your diffractometer's software to combine all images and integrate over the resultant diffraction pattern.

3. Performing Solvent-assisted Linker Exchange (SALE) on Br-YOMOF Crystals

- Weigh out 21 mg of **dped** (0.095 mmol) and dissolve it in 5 ml DMF in a 2-dram vial with ultrasonication.
- Using a 6" Pasteur pipet, collect the **Br-YOMOF** crystals and filter them on a Buchner funnel. Then weigh out ~30 mg of the crystals; return the rest of the crystals to the vial with **Br-YOMOF**.
- Disperse the crystals in the previously prepared **dped** solution. Place the resulting SALE mixture in an oven at 100 °C for 24 hr.
- On the next day, check the progress of the SALE reaction with ^1H NMR. With a spatula or a 6" Pasteur pipet, remove approximately 2-5 mg of the MOF crystals from the reaction DMF solution. Rinse these crystals by submerging them in a small amount of clean solvent (low boiling solvent such as dichloromethane, or same solvent as the reaction medium — in this case DMF) in a 1.5-dram vial.
- Add ~1 ml deuterated dimethyl sulfoxide ($\text{d}_6\text{-DMSO}$) in a separate 1.5-dram vial. Filter out the crystals from the cleaning solution and disperse them in $\text{d}_6\text{-DMSO}$. Dissolve the crystals by adding 3 drops of deuterated sulfuric acid (D_2SO_4) to the mixture. Thoroughly sonicate the capped vial to obtain a homogeneous solution.
- Transfer the resulting NMR sample to an NMR tube with a Pasteur pipet and collect the NMR spectrum. Perform 64 scans, since the solution is relatively dilute due to the low solubility of the MOF crystals.
- Interpret the spectrum by verifying that all the **dpni** has been replaced by **dped**, and that the **dped:Br-tcpb** ratio is 1:1.
NOTE: If **dpni** is still present in the crystals, return the vial with the reaction mixture to the oven and keep monitoring the reaction with ^1H NMR until the desired product is obtained.
- If all **dpni** has been replaced by **dped**, stop the reaction by decanting the reaction solution with a 9" Pasteur pipet and replacing it with fresh DMF. Perform additional characterization of the **SALEM-5** crystals by collecting their PXRD pattern; then store the crystals in DMF until further use.

4. Activating SALEM-5 Crystals with Supercritical CO_2 Drying

- Prior to activation, exchange all the DMF from the MOF cages with ethanol, which is miscible with liquid CO_2 and compatible with the supercritical dryer. Perform solvent replacement by decanting the DMF from the MOF vial with a 9" Pasteur pipet and replacing it with a small amount of ethanol (enough to completely submerge the crystals).
- Continue the solvent exchange for 3 days, replacing the ethanol with a fresh batch every day. Ensure that all the DMF has been removed from the crystal pores by collecting a ^1H NMR spectrum of the crystals.
- Check that a tank with sufficient liquid CO_2 is connected to the supercritical dryer.
- Transfer the MOF crystals to an activation dish using a 6" Pasteur pipet. Then remove as much of the ethanol as possible with a 9" Pasteur pipet while avoiding sucking the crystals up into the pipet.
- Remove the lid of the activation chamber by unscrewing the three bolts and inspect the chamber for residual MOF debris (if those are present, wipe the chamber clean with a Kimwipe). Using a pair of forceps, insert the activation dish with the MOF into the chamber and screw the lid back into its place.
- Turn the dryer on and open the CO_2 tank. Adjust the temperature knob to achieve a temperature between 0 and 10 °C. Maintain that temperature range throughout the activation process to keep CO_2 in its liquid state.
- Once the temperature is in the correct range, turn up the "fill" knob slowly. Observe liquid CO_2 pouring into the activation dish through the glass window on the chamber lid. At the same time the pressure reading on the gauge should increase until it reaches 800 psi.
- Perform the first "purge", that is the first replacement of the activation solvent with a fresh batch. First turn the "fill" knob up to the mark that reads 15. Then slowly turn up the "purge" knob until a jet of solvent shoots out from the tube on the side of the instrument. Let the purge go on for ~5 min; then close the "purge" knob and turn the "fill" knob down to the mark that reads 5.
- Continue the supercritical drying for 8 hr, performing a "purge" every 2 hr.
- After 8 hr, turn all the knobs off and flip the "heat" switch on. Wait until the temperature and pressure exceed the supercritical point (31 °C and 1,070 psi).
- Connect a flowmeter to the tube on the side of the instrument and open the "bleed" knob. Adjust the flow to 1 cm^3/min ; then remove the flowmeter and let the CO_2 slowly bleed from the sample (which typically takes place O/N).
- The next day, check that the pressure has dropped to 0 psi; if it has not, turn up the "bleed" knob until you achieve the desired pressure drop. Close the "bleed" knob and turn off the "heat" and power switches on the instrument.
- Remove the sample from the activation chamber. Cap the activation dish tightly and wrap it in Parafilm. Store the activated **SALEM-5** in a glove box until further use. Make sure that no ethanol is present in the sample by collecting a ^1H NMR spectrum.

5. Collecting a N_2 Isotherm of the MOF to Obtain Its BET Surface Area

- Obtain a sorption tube equipped with a filler rod and a seal frit and accurately weigh it. Weigh it at least two times and make sure the two balance readings agree with each other within ± 0.01 mg.
- Transfer the pre-weighed tube to the glove box and load the activated **SALEM-5** sample inside the tube. We recommend using a clean, dry funnel, as activated MOF samples stored in the glove box are often electrostatically charged and difficult to handle. Remove the seal frit and the filler rod from the tube and fit it with a funnel; then rapidly invert the activation dish over the funnel, making sure the sample slides down the tube.
- Reinsert the filler rod and the seal frit into the tube loaded with **SALEM-5**. Slide the filler rod slowly and carefully into the tube to avoid spilling the sample and/or breaking the tube. Remove the tube from the glove box.
- Weigh the loaded tube accurately, using the same technique (and the same balance) that you used to load the empty tube.
- Place an isothermal jacket on the tube, load the tube on the sorption instrument and set up the sorption file by entering the masses of the empty tube and the tube with the sample. Adjust the file to evacuate the sample on the instrument for 1 hr prior to the collection of the isotherm.

6. Ensure that the Dewar used to store the liquid nitrogen is free from ice and/or water by filling it with water to allow the ice to thaw and then wiping it dry. Fill the Dewar with liquid nitrogen to the appropriate mark and start the measurement. The measurement lasts anywhere from 4 to 12 hr, depending on the amount and the porosity of the material.

Representative Results

The use of HCl during MOF synthesis is often beneficial for the growth of high quality MOF crystals. As it slows down the deprotonation of the carboxylate (and the binding of the linkers to the metal centers), it promotes growth of larger crystals and prevents formation of amorphous and polycrystalline phases, which may form if the reaction is allowed to proceed more rapidly. In fact, as it can be seen in **Figure 3**, the pillared-paddlewheel MOFs that are produced during this reaction form large, yellow crystals of sufficient quality for single crystal data collection. Furthermore, the use of HCl in conjunction with a high-boiling, polar solvent facilitates the dissolution of the MOF linkers for the creation of the reaction mixture (the polyacids and some of the long nitrogen donor pillars can be challenging to dissolve). However, incorporation of pillars possessing free coordinating functional groups (such as **dped**) into MOFs is not as facile as incorporation of unfunctionalized pillars such as **dpni**. As can be seen from **Figure 4**, when the protocol that was used to synthesize **Br-YOMOF** is applied to the synthesis of **SALEM-5**, the ^1H NMR of the resulting product shows complete absence of **dped** from the crystals (and presumably formation of $\text{Zn}_2(\text{Br-tcpb})(\text{DMF})_2$ instead of the desired product). To halt the interaction of the functionalized linker with the reactive MOF components (such as the metal precursors), we have to resort to SALE to access **SALEM-5**. We have found that the pK_a of the monoprotonated conjugate acid of the pillar serves as a useful indicator of the strength with which the pillar is bound to the binuclear metal cluster.¹⁸ **dpni** is a relatively acidic, weakly bound pillar, and it is readily replaced by various other pillars, including **dped**. A typical SALE involving **dpni** as a leaving pillar requires less than 24 hr, with >99% of the pillar being replaced, as is indicated by ^1H NMR.

As far as the characterization of the crystals is concerned, it is crucial to have accurate information about the bulk crystallinity of the product, which is conveyed by a successfully collected PXRD pattern. Obtaining PXRD patterns of pillared-paddlewheel MOFs is not a straightforward procedure, however, since these materials tend to lose crystallinity when their crystals dry (the crystallinity can be recovered by solvating the crystals). As a result, conventional PXRD techniques that employ mounting the material on a glass slide will produce a pattern that may not contain all the peaks one expects to find in the pattern from the simulated data. Moreover, pillared-paddlewheel crystals are highly anisotropic, as they are significantly more elongated in the direction of the c-axis (along which the nitrogen donor pillars lie) than in the a-b plane (where the 2-D sheets that contain the paddlewheel structural building units are found). This crystal morphology often leads to preferential orientation of the crystals during conventional PXRD measurements, with the result of several of the reflections exhibiting an unusually high intensity in the pattern (**Figure 5**). Both these problems are avoided if PXRD is taken on crystals in solution using a spinning capillary.²⁷ Not only does this technique allow the collection of a representative PXRD pattern, but it also requires significantly less material than conventional methods (~1 mg). Therefore, when working with pillared-paddlewheel MOFs, we always characterize their crystallinity by running PXRD measurements in spinning capillaries. Due to the anisotropic morphology of pillared-paddlewheel MOFs, analysis of their PXRD patterns can provide important information about the size of their nitrogen donor pillars. The peak corresponding to the reflection coming from the direction of the c-axis is the first peak in the pattern (for **Br-YOMOF**, the [001] reflection). The position of the first peak at a lower 2θ angle signifies the presence of a larger unit cell in the direction of the c-axis (and therefore, a longer nitrogen donor pillar).

Finally, activation of pillared-paddlewheel (and other carboxylate-based) MOFs by supercritical drying has proven to provide access to significantly higher BET surface areas than those accessed by conventional activation techniques (heating under vacuum and solvent exchange, or the combination of the two).²³ **Figure 6** shows images of the crystals of **NU-100**, a MOF with paddlewheel-based structural building units, upon conventional heat and vacuum activation (dark, amorphous particles) and upon supercritical CO_2 drying (teal crystals). While the former procedure leads to framework collapse and destruction of porosity, supercritical CO_2 drying leads to a BET surface area of ~6140 m^2/g .²⁴ To summarize, it provides a gentle activation method that allows accessing the porosity of some of the more delicate MOFs (pillared-paddlewheel materials, Zn_4O -based IRMOFs, ultrahigh porosity MOFs of *rht* topology, etc.).¹³

$2\theta(^{\circ})$	$\omega(^{\circ})$	$\chi(^{\circ})$
12	6	0
24	12	0
36	18	0
48	24	0
60	30	0

Table 1. Parameters for collecting 180° ϕ scans for performing powder X-ray diffraction in capillaries.

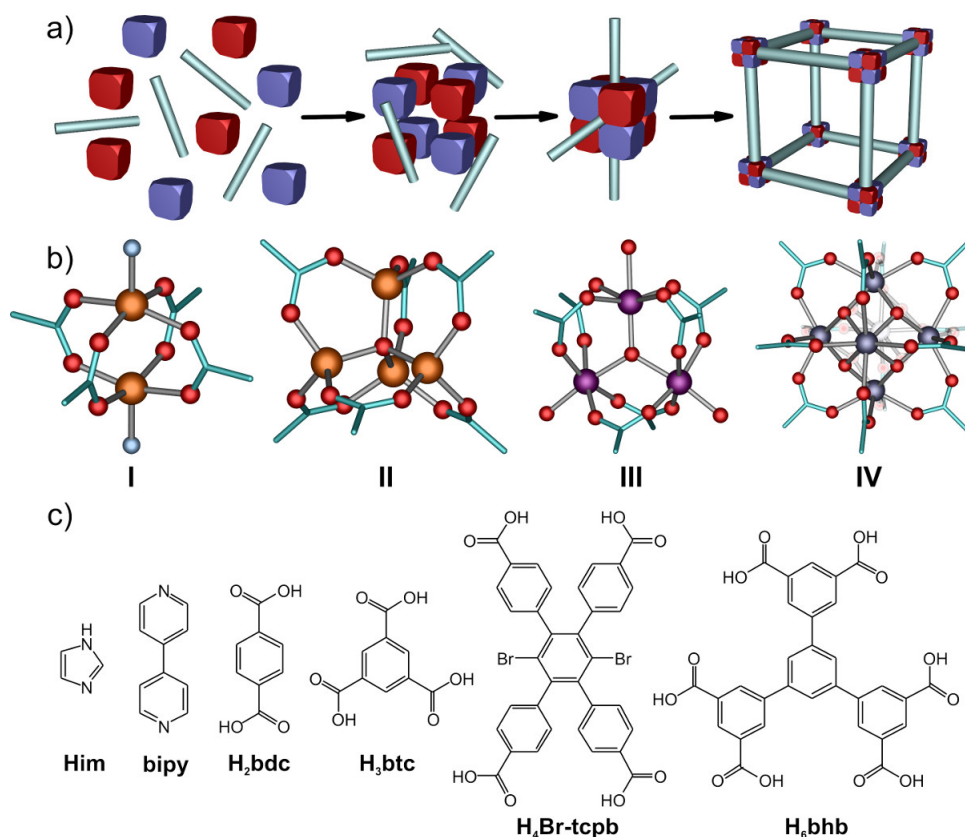


Figure 1. (A) Representation of the solvothermal MOF synthesis process. (B) Examples of metal-based structural building units (from left to right, $\text{Zn}_2(\text{COO})_4$, Zn_4O^{6+} , $\text{Cr}_3(\text{H}_2\text{O})_2\text{OF}^{6+}$, $\text{Zr}_6\text{O}_4(\text{OH})_4^{12+}$). (C) Representative linkers used for MOF synthesis (**Him** = imidazole; **bipy** = 4,4'-bipyridine; **H₂bdc** = benzene-1,4-dicarboxylic acid; **H₃btc** = benzene-1,3,5-tricarboxylic acid; **H₄Br-tcpb** = protonated 1,4-dibromo-2,3,5,6-tetrakis-(4-carboxyphenyl)benzene; **H₆bhb** = 3,3',3'',5,5',5''-benzene-1,3,5-triyl-hexabenzoic acid). [Please click here to view a larger version of this figure.](#)

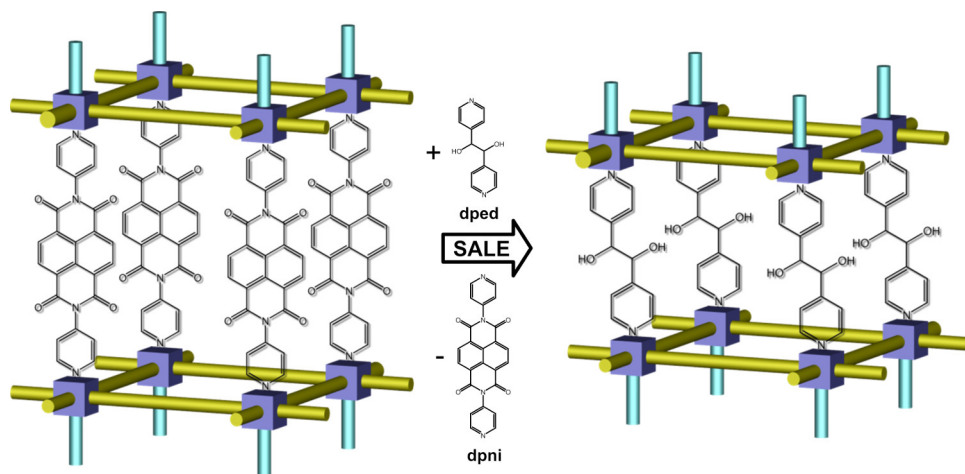


Figure 2. SALE of the Br-tcpb linker in Br-YOMOF to dped to produce SALEM-5. [Please click here to view a larger version of this figure.](#)

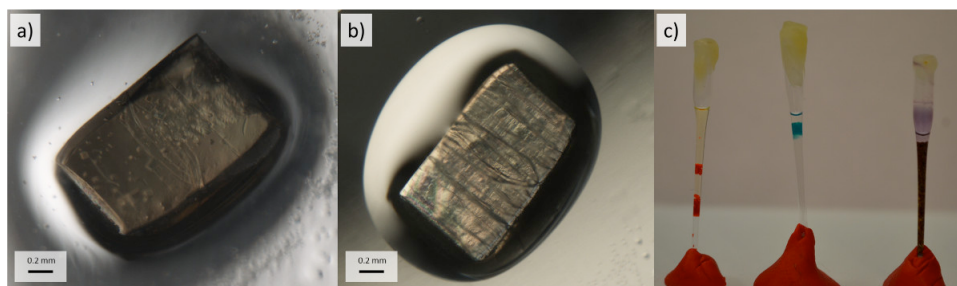


Figure 3. (A-B) Images of a single crystal of **Br-YOMOF** (A) and the same crystal transformed to **SALEM-5** after 24 hr of SALE reaction with **dped** (B). As is the case with single crystal-to-single crystal reactions, the size and the morphology of the crystal did not change. (C) Photograph of capillaries typically used in PXRD measurements. [Please click here to view a larger version of this figure.](#)

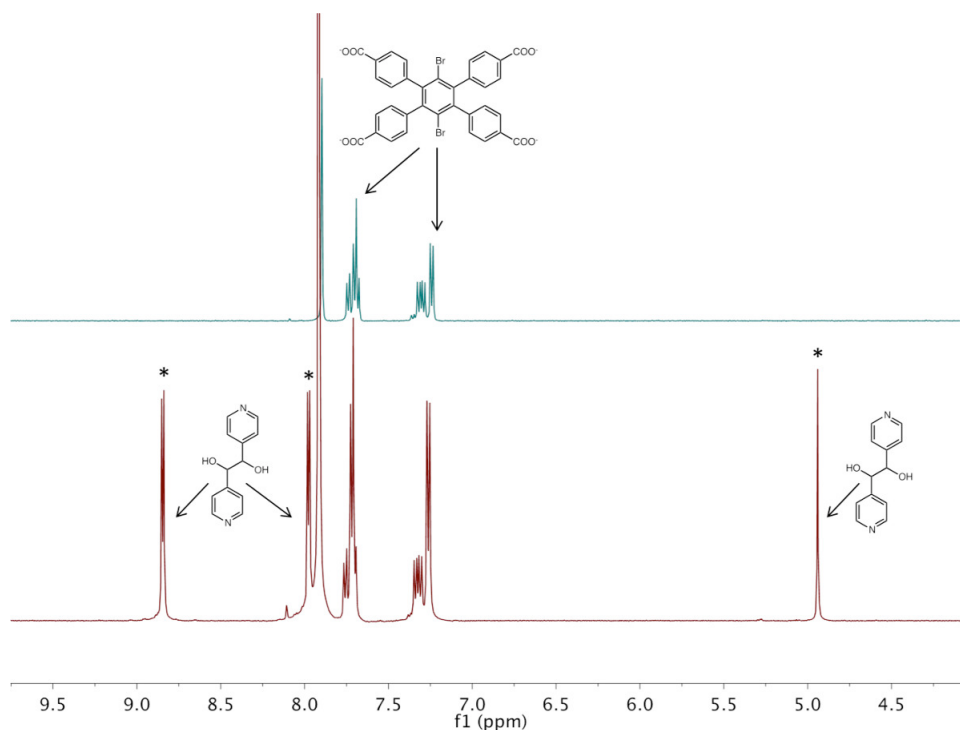


Figure 4. ¹H NMR spectra of the digested MOF crystals resulting from different synthetic attempts to access **SALEM-5**. (top) ¹H NMR spectrum of the product of the *de novo* method (following the same protocol as that used for the *de novo* synthesis of **Br-YOMOF**). (bottom) ¹H NMR spectrum of the product of the SALE method. The peaks marked with asterisks represent signals resulting from **dped**. The spectra show that the *de novo* attempt resulted in the lack of incorporation of the **dped** pillars into the crystals; the SALE attempt, on the other hand, led to successful formation of the desired product (with the **Br-tcpb:dped** ratio 1:1). [Please click here to view a larger version of this figure.](#)

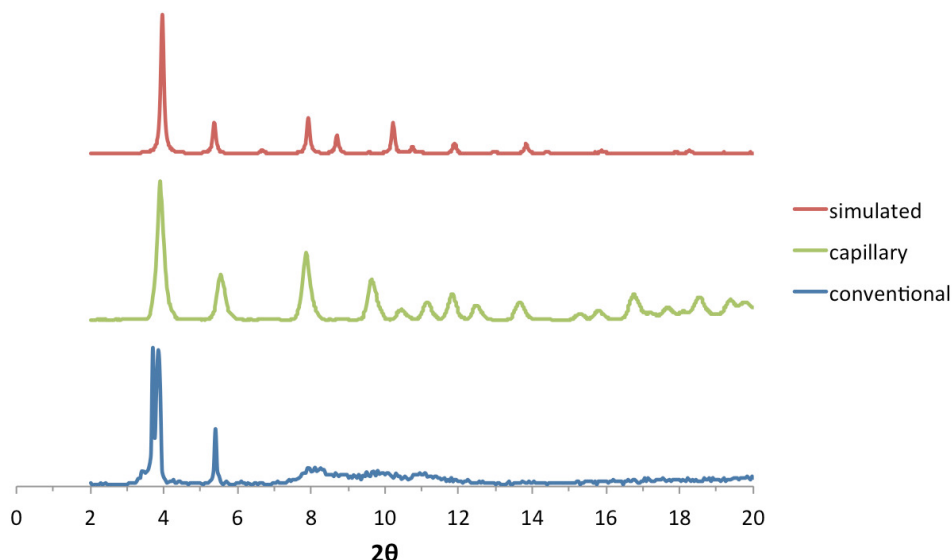


Figure 5. PXRD patterns of **Br-YOMOF** obtained by placing the sample in a spinning capillary filled with solvent (middle) and utilizing the conventional PXRD pattern collection method, which employs mounting the ground sample on a glass slide (bottom). When **Br-YOMOF** is mounted on a slide, its crystalline powder gradually dries out and loses crystallinity, which is manifested in the loss of peaks at higher angles. This problem is avoided by employing spinning capillaries, which allow collection of the PXRD pattern featuring all the peaks expected to be present for **Br-YOMOF** from its simulated pattern. [Please click here to view a larger version of this figure.](#)

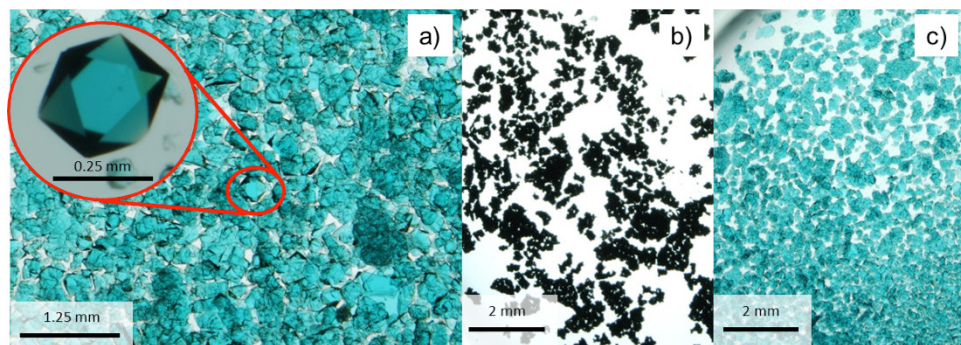


Figure 6. (A) Crystals of as-synthesized **NU-100**. (B) **NU-100** crystals after activation by conventional vacuum heating showing visible structural collapse. (C) **NU-100** crystals after supercritical CO_2 drying with the framework intact. [Please click here to view a larger version of this figure.](#)

Discussion

MOF crystallization is a delicate procedure that can be inhibited by even slight variations in the multiple parameters that describe the synthetic conditions. Therefore, special care needs to be taken when preparing the reaction mixture. The purity of the organic linkers should be confirmed by ^1H NMR prior to the onset of the synthesis, as the presence of even small amounts of impurities is known to prevent crystallization altogether or result in the formation of undesired crystalline products. Polar, high-boiling solvents such as DMF, *N,N*'-dimethylacetamide (DMA), *N,N*'-diethylformamide (DEF) or *n*-butanol provide optimal reaction media for MOF synthesis, as they remain liquid at the temperatures at which crystallization occurs (typically 60–150 °C), while at the same time most reagents can dissolve in them. When choosing the right solvent, one must take into consideration the stability of the reagents in basic conditions; for example, it is known that at elevated temperatures DMF decomposes to form dimethylamine, so a MOF containing linkers that cannot tolerate amines should not be synthesized in this solvent. The temperature should be maintained constant throughout the reaction; an oven with a door that closes tightly is an ideal incubator for MOF crystallization.

Once the MOF crystals have grown, they must be properly harvested and purified. Since MOFs are highly porous materials, the cages and channels in their freshly synthesized crystals are typically filled with residue from the reaction medium — solvent molecules, unreacted linkers, *etc.* Mere washing with organic solvents is not sufficient to dislodge these trapped components; a prolonged exposure (soaking) in a clean solvent is necessary to achieve diffusion of the impurities from the pores of the MOF. Periodic replacement of the solvent is recommended for maintaining the right chemical potential to ensure more effective purification.²⁸ Transferring the crystals to the soaking solution should also be done with care. More robust MOFs (e.g., ZIFs,¹ MILs,²⁹ UiOs³⁰) may be filtered prior to solvent exchange; however, fragile frameworks are best preserved when drying out of the crystals (which may be induced by vacuum filtration) is avoided. Therefore, removal of the excess reaction medium solvent by decantation is instead recommended.

The process of accessing MOFs by SALE deserves a special discussion. Since SALE is a single crystal-to-single crystal process, the parent MOF crystals will not appear morphologically altered after complete linker exchange has taken place; therefore, unless colored linkers are

employed, there are no visual cues that indicate the completion of SALE. As a result, careful monitoring of the SALE reaction by NMR is necessary. The low solubility of MOFs in common organic solvents leads to several caveats that need to be addressed when preparing samples for NMR measurements. MOFs typically call for the use of the more polar d_7 -DMF or d_6 -DMSO (the cheaper alternative). These solvents still need to be supplemented with D_2SO_4 , ample sonication and sometimes heating to achieve the formation of a homogeneous solution that can serve as a reliable NMR sample. When interpreting the NMR spectrum of a pillared-paddlewheel MOF, particular care needs to be taken to verify that the tetraacid:pillar ratio is close to 1 — that is, no carboxylate linker leaching has occurred, and all the pillar signals come from coordinated pillars, rather than pillars simply lodged in the pores.

During pillared-paddlewheel MOF activation, the same principle applies as during the handling of MOFs in general — the crystals should not be allowed to rapidly dry. This is why the crystals are introduced into the activation chamber dispersed in a small amount of ethanol (just enough to completely cover them), and meticulous care is taken to maintain CO_2 in its liquid phase throughout the activation. Some activated samples may be extremely sensitive to air and humidity. Diffusion of water molecules into their channels may detriment their surface area; moreover, if open metal sites are present within the MOF, the water molecules will bind to them and extinguish their reactive properties. Water is also known to compete with the nitrogen pillars for the binuclear metal centers, and has been observed to displace even strongly bound pillars such as 1,4-diazabicyclo[2.2.2]octane (**dabco**) from the framework.³¹ For that reason, most activated pillared-paddlewheel MOFs should be stored in the glove box. When these activated samples are transferred between storage places and instruments, they should be in tightly sealed (e.g., Parafilm) containers. Sorption tubes containing these samples should be fitted with air-tight seal frits.

Finally, two points must be addressed concerning the measurement of BET surface areas. First, the importance of obtaining an accurate mass of the measured activated sample cannot be emphasized enough, especially when dealing with small amounts of materials. One can become convinced in the reliability of their measurements by weighing the sample multiple times prior to beginning the measurements and obtaining the same mass, and by collecting multiple isotherms from different batches of the same MOF and obtaining the same surface area. Secondly, since most MOFs (including pillared-paddlewheel MOFs) are microporous materials, there are specific rules when it comes to selecting the appropriate branch of the adsorption isotherm used for the calculation of the BET surface area. The selected points should satisfy the criteria outlined by Snurr and coworkers in their seminal work.³² These points are typically found in much lower pressures than the ones used for the calculations of BET surface areas of meso- and macroporous materials — namely at the relative pressure P/P_0 of 0.005–0.05. Moreover, Langmuir surface areas, which assume the formation of a monolayer of the adsorbent, are not appropriate for assessing the porosity of microporous materials; BET surface areas should always be used.

The protocols described herein provide some helpful methods for MOF synthesis, characterization and activation towards gas sorption applications. Their application can yield otherwise difficult to synthesize MOFs, prevent their delicate frameworks from degradation during their study and allow access to their evacuated pores. We hope that this information will be of use to researchers that are interested in investigating this exciting and intellectually stimulating area.

Disclosures

The authors have nothing to disclose.

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References

- Phan, A. *et al.* Synthesis, Structure, and Carbon Dioxide Capture Properties of Zeolitic Imidazolate Frameworks. *Acc. Chem. Res.* **43**, 58-67 (2009).
- Furukawa, H., Cordova, K. E., O'Keeffe, M., & Yaghi, O. M. The Chemistry and Applications of Metal-Organic Frameworks. *Science*. **341** (2013).
- Farha, O. K. *et al.* Metal–Organic Framework Materials with Ultrahigh Surface Areas: Is the Sky the Limit? *J. Am. Chem. Soc.* **134**, 15016-15021 (2012).
- Suh, M. P., Park, H. J., Prasad, T. K., & Lim, D.-W. Hydrogen Storage in Metal–Organic Frameworks. *Chem. Rev.* **112**, 782-835 (2011).
- Sumida, K. *et al.* Carbon Dioxide Capture in Metal–Organic Frameworks. *Chem. Rev.* **112**, 724-781 (2011).
- Liu, J., Thallapally, P. K., McGrail, B. P., Brown, D. R., & Liu, J. Progress in adsorption-based CO_2 capture by metal-organic frameworks. *Chem. Soc. Rev.* **41**, 2308-2322 (2012).
- Lee, J. *et al.* Metal-organic framework materials as catalysts. *Chem. Soc. Rev.* **38**, 1450-1459 (2009).
- Yoon, M., Srirambalaji, R., & Kim, K. Homochiral Metal–Organic Frameworks for Asymmetric Heterogeneous Catalysis. *Chem. Rev.* **112**, 1196-1231 (2011).
- Kreno, L. E. *et al.* Metal–Organic Framework Materials as Chemical Sensors. *Chem. Rev.* **112**, 1105-1125 (2011).
- Chen, B., Xiang, S., & Qian, G. Metal–Organic Frameworks with Functional Pores for Recognition of Small Molecules. *Acc. Chem. Res.* **43**, 1115-1124 (2010).
- Wang, J.-L., Wang, C., & Lin, W. Metal–Organic Frameworks for Light Harvesting and Photocatalysis. *ACS Catalysis*. **2**, 2630-2640 (2012).
- Lewis, D. W. *et al.* Zeolitic Imidazole Frameworks: Structural and Energetics Trends Compared with their Zeolite Analogues. *CrystEngComm*. **11**, 2272-2276 (2009).
- Mondloch, J. E., Karagiari, O., Farha, O. K., & Hupp, J. T. Activation of metal-organic framework materials. *CrystEngComm*. **15**, 9258-9264 (2013).

14. Karagiari, O. *et al.* Synthesis and characterization of isostructural cadmium zeolitic imidazolate frameworks via solvent-assisted linker exchange. *Chemical Science*. **3**, 3256-3260 (2012).
15. Burnett, B. J., Barron, P. M., Hu, C., & Choe, W. Stepwise Synthesis of Metal–Organic Frameworks: Replacement of Structural Organic Linkers. *J. Am. Chem. Soc.* **133**, 9984-9987 (2011).
16. Kim, M., Cahill, J. F., Su, Y., Prather, K. A., & Cohen, S. M. Postsynthetic ligand exchange as a route to functionalization of "inert" metal-organic frameworks. *Chemical Science*. **3**, 126-130 (2012).
17. Bury, W. *et al.* Control over Catenation in Pillared Paddlewheel Metal–Organic Framework Materials via Solvent-Assisted Linker Exchange. *Chem. Mater.* **25**, 739-744 (2013).
18. Karagiari, O. *et al.* Opening Metal–Organic Frameworks Vol. 2: Inserting Longer Pillars into Pillared-Paddlewheel Structures through Solvent-Assisted Linker Exchange. *Chem. Mater.* **25**, 3499-3503 (2013).
19. Li, T., Kozłowski, M. T., Doud, E. A., Blakely, M. N., & Rosi, N. L. Stepwise Ligand Exchange for the Preparation of a Family of Mesoporous MOFs. *J. Am. Chem. Soc.* (2013).
20. Karagiari, O. *et al.* Opening ZIF-8: A Catalytically Active Zeolitic Imidazolate Framework of Sodalite Topology with Unsubstituted Linkers. *J. Am. Chem. Soc.* **134**, 18790-18796 (2012).
21. Takaishi, S., DeMarco, E. J., Pellin, M. J., Farha, O. K., & Hupp, J. T. Solvent-assisted linker exchange (SALE) and post-assembly metallation in porphyrinic metal-organic framework materials. *Chemical Science*. **4**, 1509-1513 (2013).
22. Vermeulen, N. A. *et al.* Aromatizing Olefin Metathesis by Ligand Isolation inside a Metal–Organic Framework. *J. Am. Chem. Soc.* **135**, 14916-14919 (2013).
23. Nelson, A. P., Farha, O. K., Mulfort, K. L., & Hupp, J. T. Supercritical Processing as a Route to High Internal Surface Areas and Permanent Microporosity in Metal–Organic Framework Materials. *J. Am. Chem. Soc.* **131**, 458-460 (2008).
24. Farha, O. K. *et al.* De novo synthesis of a metal–organic framework material featuring ultrahigh surface area and gas storage capacities. *Nat Chem.* **2**, 944-948 (2010).
25. Furukawa, H. *et al.* Ultrahigh Porosity in Metal-Organic Frameworks. *Science*. **329**, 424-428 (2010).
26. Farha, O. K., Malliakas, C. D., Kanatzidis, M. G., & Hupp, J. T. Control over Catenation in Metal–Organic Frameworks via Rational Design of the Organic Building Block. *J. Am. Chem. Soc.* **132**, 950-952 (2009).
27. Shultz, A. M., Sarjeant, A. A., Farha, O. K., Hupp, J. T., & Nguyen, S. T. Post-Synthesis Modification of a Metal–Organic Framework To Form Metallosalen-Containing MOF Materials. *J. Am. Chem. Soc.* **133**, 13252-13255 (2011).
28. Li, H., Eddaoudi, M., O'Keeffe, M., & Yaghi, O. M. Design and synthesis of an exceptionally stable and highly porous metal-organic framework. *Nature*. **402**, 276-279 (1999).
29. Ferey, G. *et al.* Chromium Terephthalate-Based Solid with Unusually Large Pore Volumes and Surface Area. *Science*. **309**, 2040-2042 (2005).
30. Cavka, J. H. *et al.* A New Zirconium Inorganic Building Brick Forming Metal Organic Frameworks with Exceptional Stability. *J. Am. Chem. Soc.* **130**, 13850-13851 (2008).
31. Chen, Z., Xiang, S., Zhao, D., & Chen, B. Reversible Two-Dimensional–Three Dimensional Framework Transformation within a Prototype Metal–Organic Framework. *Crystal Growth, & Design*. **9**, 5293-5296 (2009).
32. Walton, K. S., & Snurr, R. Q. Applicability of the BET Method for Determining Surface Areas of Microporous Metal–Organic Frameworks. *J. Am. Chem. Soc.* **129**, 8552-8556 (2007).