

Benign by Design: Green and Scalable Synthesis of Zirconium UiO- Metal-Organic Frameworks by Water-Assisted Mechanochemistry

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ABSTRACT: We present a solvent-free, green and rapid mechanochemical route for the synthesis of a series of zirconium metal-organic frameworks (MOFs) comprised of Zr₆-cluster nodes, UiO-66, UiO-66-NH₂, MOF-801 and MOF-804, both on a laboratory scale and by scalable and flow mechanochemical processing. The methodology, based on the use of a non-conventional

zirconium dodecanuclear acetate cluster and a minute amount of water as an additive, affords high-quality MOFs in less than an hour of milling, with minimal requirements for work-up processing and eliminating the need for conventional hazardous solvents, such as dimethylformamide. Moreover, the use of a dodecanuclear zirconium acetate precursor circumvents the need for modulators resulting in acetic acid as the only byproduct of the reaction, which does not harm these acid-resistant materials. The porosity, thermal and chemical stability, as well as catalytic activity of mechanochemically prepared Zr-based MOFs are similar to those of solvothermally synthesized counterparts. Finally, the synthesis is readily applicable on a 10-gram scale by using planetary mill, and is also performed by solid-state flow synthesis using twin-screw extrusion (TSE), affording more than 100 g of catalytically active UiO-66-NH₂ material in a continuous process at a rate of 1.4 kg/h.

Keywords: Zirconium MOFs, zirconium acetate precursor, mechanochemistry, simple activation procedures, twin-screw extrusion, catalytic activity

INTRODUCTION

There is a growing interest in the synthesis and design of metal–organic frameworks (MOFs) as highly tunable, microporous functional materials for uses in gas storage, separation, catalysis and more.^{1–4} Among diverse MOF designs, zirconium-based architectures with [Zr₆O₄(OH)₄]¹²⁺ cluster nodes and bridging carboxylate linkers are particularly attractive for their high chemical and thermal stability, including resistance to water,^{5,6} high surface area, biocompatibility,^{7,8} and excellent catalytic activity,^{1,9,10} *e.g.* in detoxification of chemical warfare agents and simulants.¹¹ The archetypal zirconium MOFs of the UiO-family¹, which are based on 12-connected metal nodes and adopt the *fcu*-topology, are particularly noted for their catalytic activity - which can be

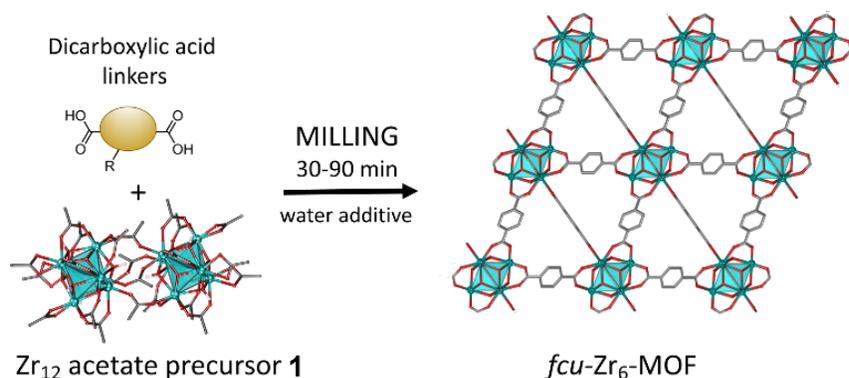
enhanced by the introduction of electron withdrawing groups on the linker,^{12,13} or by the controlled introduction of defects (e.g. missing linkers or missing nodes).^{12,14}

Despite recent commercialization,¹⁵ wider use of MOFs is hindered by long, often costly synthetic procedures^{16,17} which commonly involve high-boiling and hazardous organic solvents such as *N,N*-dimethylformamide (DMF), *N,N*-dimethylacetamide (DMA), as well as soluble nitrate or chloride metal salts, combined with acidic modulators, long reaction times, and large amounts of waste by-products which need to be remediated and/or recycled.^{1,18,19} In contrast to process chemistry and organic synthesis, which have placed strong focus on the development of cleaner, safer and sustainable reactions and techniques, there has been much less attention to such development in the context of coordination chemistry and MOF synthesis. Recently, however, a number of studies have begun to address the need for new, greener procedures for preparation of metal-organic materials.^{20,21}

Mechanochemistry,^{22,23} *i.e.* chemical reactivity induced by mechanical force, has surfaced as a versatile technique for conducting clean, solvent-free reactions in a wide range of areas, including organic,^{24–30} pharmaceutical,^{31,32} inorganic,^{33–37} organometallic,^{38–40} supramolecular^{41–46} and coordination^{47–50} chemistry. Indeed, over the past decade mechanochemistry has provided efficient, rapid routes for the assembly of coordination polymers and microporous MOFs, without resorting to solvents or high temperatures common in solvothermal synthesis, and often from simple, readily accessible reagents.^{51–54} Particularly useful in that context are liquid-assisted grinding (LAG), which uses a small amount of a liquid phase to accelerate reactivity, template the structure, and ensure a high degree of crystallinity of the product,^{55–57} and ion- and liquid-assisted grinding (ILAG), which also uses a catalytic amount of a salt to enable MOF assembly from typically inert metal oxides.^{58,59} The introduction of LAG and ILAG methods has enabled rapid

progress in mechanochemical MOF synthesis, with reliable, rapid room-temperature procedures reported for a number of popular MOFs, including IRMOF-1,⁵⁸ MOF-74,⁶⁰ MIL-100,⁶¹ Al(fumarate)(OH)⁵ and UiO-66.^{9,62} While all these reports highlight quantitative reactions yields achieved at room temperature and in significantly less time compared to most conventional solution-based or solvothermal processes (30-60 minutes compared to days), they nevertheless require the use of minuscule amounts of organic liquid additives.

We now demonstrate the next step in achieving a cleaner, safer, as well as scalable access to useful MOF products, by developing a generally applicable mechanochemical synthesis of high-performance zirconium MOFs based on Zr₆-cluster nodes, UiO-66, UiO-66-NH₂, MOF-801 and MOF-804, requiring the use of only water as the LAG liquid additive. Whereas the synthesis of a UiO-66 derivative by water-assisted milling was recently reported, the procedure was limited only to the fluorinated framework UiO-66-F₄.⁶³ Central to the herein presented procedure are the stability of zirconium MOFs in aqueous environments and the use of a non-conventional dodecanuclear zirconium acetate cluster Zr₁₂O₈(OH)₈(CH₃COO)₂₄, (**1**) as a precursor. This compound is readily prepared on a 100 g scale from Zr(IV) propoxide and acetic acid (Scheme 1). While the MOF materials prepared by this procedure exhibit porosity and catalytic activity comparable to the conventionally-prepared counterparts, the reactions provide the environmental benefit of generating acetic acid as the only by-product, and are readily scalable to multi-gram amounts by using a planetary mill. In case of UiO-66-NH₂, a MOF of high activity for catalytic breakdown of nerve gas simulants, this mechanochemical procedure was adapted for continuous twin screw extrusion (TSE)^{5,64-66} manufacture at a rate of almost 1.4 kg/h.



Scheme 1. Water-assisted mechanochemical procedure for green synthesis of zirconium MOFs.

RESULTS AND DISCUSSION

The first reported mechanochemical syntheses of UiO-66 and UiO-66-NH₂ relied on the use of a pre-synthesized Zr₆ methacrylate cluster⁹ **2** as the precursor, in the presence of small volumes of DMF or methanol (MeOH) as LAG additives. Notably, **2** was also shown to be an efficient precursor for the water-assisted milling synthesis of the fluorinated UiO-66 analogue UiO-66-F₄.⁶³ However, the water-assisted synthesis was limited only to UiO-66-F₄, which was tentatively ascribed to the higher solubility of fluoroterephthalic acid in water compared to other terephthalic acid linkers. Whereas the use of **2** enables rapid and efficient synthesis of several UiO-materials, it also involves certain environmental and safety concerns due to release of methacrylic acid during the reaction. In particular, methacrylic acid is considered a hazardous, corrosive and reactive substance by the National Institute for Occupational Safety and Health (NIOSH) and the US Occupational Safety and Health Administration (OSHA).⁶⁷ Released methacrylic acid also provides a potential polymerization link upon milling in presence of water. Such polymerization could tentatively lead to clogging of MOF pores, requiring complicated purification procedures and diminishing the product quality. The herein presented results demonstrate that the dodecanuclear zirconium acetate cluster **1** can be used as an efficient, and more broadly applicable

precursor for mechanochemical synthesis of UiO-type MOFs, at the same time avoiding the generation of reactive and hazardous methacrylic acid byproduct.

Water-assisted milling synthesis from the methacrylate cluster 2

In order to evaluate the relative efficiencies of **1** and **2** as precursors for the synthesis of UiO-type materials, we first explored the synthesis of UiO-66, UiO-66-NH₂, MOF-804 and MOF-801 from methacrylate cluster **2** using the water-assisted milling procedure. As established by Fourier-transform infrared spectroscopy (FTIR) and powder X-ray diffraction (PXRD), water-assisted milling reactions ($\eta(\text{H}_2\text{O})=0.36 \mu\text{L}/\text{mg}$) of 1:6 stoichiometric mixtures of **2** with terephthalic acid (tpa), 2-aminoterephthalic acid (atpa), 2,5-dihydroxyterephthalic acid (dhta), and fumaric acid (fum) produced either only a physical mixture of reactants, or a mixture of reactants with low amount of product (please check ESI). Specifically, the procedure was successful only for the synthesis of MOF-801, based on the short fumaric acid linker (Figure 1a). After thorough washing with water, the purity of mechanochemically synthesized MOF-801 was tested by NMR analysis. ¹H NMR of MOF-801 suspended in deuterated chloroform revealed that the product contained methacrylic acid residues that could not be completely removed by simple work-up procedures (Figure 1b).

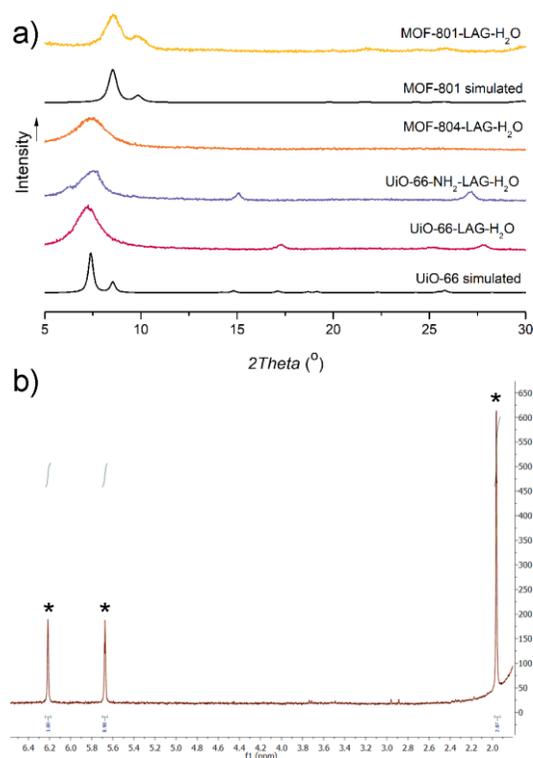


Figure 1. a) Comparison of PXRD patterns for products obtained by water-assisted grinding using methacrylate cluster **2** precursor; and b) Section of ¹H NMR data in chloroform-*d*₁ for MOF-801 product obtained from **2** collected after work-up procedure. The peaks for methacrylic acid residues are noted with asterisk. For a more detailed NMR spectrum please check Supporting Information.

Water-assisted milling synthesis from the acetate cluster **1**

After exploring methacrylate **2** as the precursor for mechanochemical synthesis of UiO-type MOFs, we turned to the dodecanuclear zirconium acetate cluster **1** as the starting material. Compound **1** was previously used for solvothermal⁶⁸ synthesis of the biphenyl-based UiO-67^{1,69} and, very recently, we have shown its use for rapid mechanochemical synthesis of high-porosity NU-901⁷⁰ and UiO-67 MOFs using DMF as the additive.⁷¹

Here, milling of **1** with twelve equivalents of bridging ligand and with water as a liquid additive in laboratory IST-500 mixer mill (InSolido Technologies) afforded UiO-66-NH₂, MOF-804 and MOF-801 in high yield after 45-90 minutes milling and simple washing with small volumes of water or methanol (Figure 2a). However, the same procedure yielded only poorly crystalline framework UiO-66, and the reaction mixture contained significant amount of unreacted ligand, even after 300 minutes of uninterrupted milling (please check Supporting Information). In order to resolve this problem, we attempted to activate the terephthalic acid reactant by addition of triethylamine (TEA) to the reaction mixture. The modified reaction procedure was conducted in two successive mechanochemical steps, by first milling TEA and terephthalic acid in 2:1 stoichiometric ratio over 30 minutes, followed by addition of **1** and milling for further 90 minutes. After washing with MeOH, the product was identified by PXRD as highly crystalline UiO-66 target (Figure 2a).

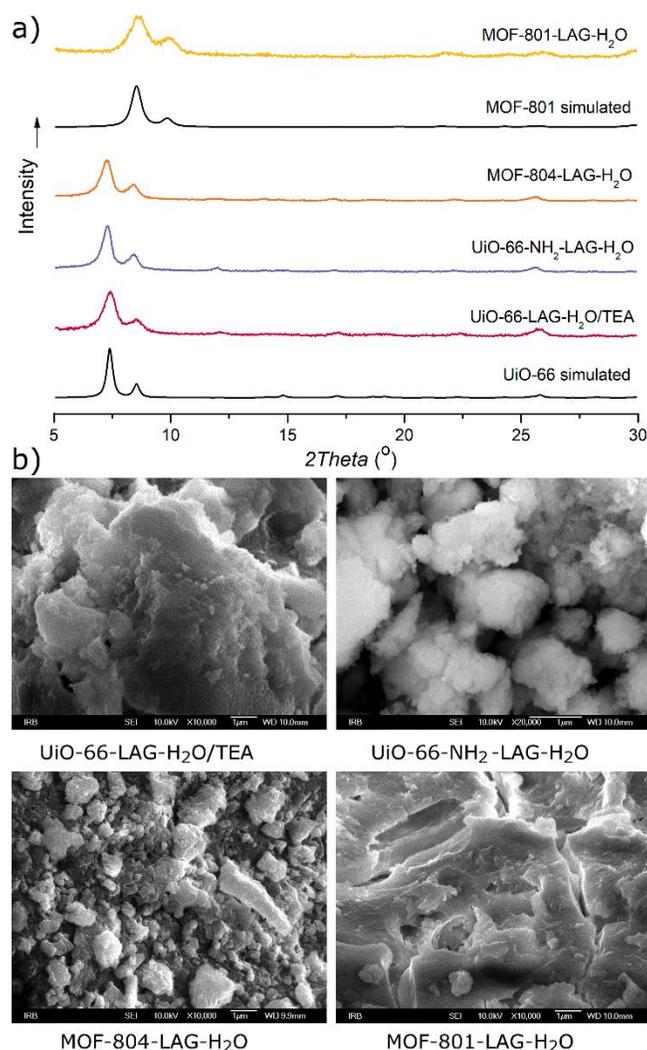


Figure 2. a) PXRD patterns for UiO- products obtained by LAG-H₂O synthesis of (from top to bottom) MOF-801, calculated pattern of MOF-801, MOF-804, UiO-66-NH₂, UiO-66, and calculated pattern of UiO-66. b) SEM micrographs for UiO-MOF derivatives prepared by water-assisted mechanochemical procedure using cluster **1**.

Scanning electron microscopy (SEM) analysis showed that in most cases milling with acetate cluster **1** afforded MOFs with particle size below 100 nm, which agglomerate to form loosely bound spherical conglomerates with ca. 1 µm diameter, as in UiO-66-NH₂ and MOF-804; or leaf-like formations in MOF-801 and UiO-66, where the MOF particles seem strongly bound (Figure

2b). Thermal decomposition of each MOF was investigated by thermogravimetric analysis (TGA) and the results were consistent with solvothermally prepared compounds. The first step of each TGA curve shows the loss of solvent and is followed by degradation of MOF, occurring between 350-500 °C. The residue above 600 °C is assumed as ZrO₂ and was confirmed by PXRD (please check SI).

The applicability of **1** for development of the green synthesis of zirconium MOFs on a multigram scale was tested on UiO-66-NH₂, one of the most potent and investigated zirconium catalysts today. Here, we devised the mechanochemical procedure to scale the reaction to 10 grams using a planetary Fritsch Pulverisette 6 reactor equipped with one 50 mL zirconia jar. 90 minutes milling with 4 mL of water additive at 500 rpm yielded more than 11 g of pale-yellow powder which was identified by PXRD as highly crystalline UiO-66-NH₂ (Figure 3). The crude product was washed with small amount of methanol to remove the acetic acid byproduct and linker residues and was further subjected to porosity measurements.

Continuous mechanochemical procedure for the synthesis of UiO-66-NH₂ by twin-screw extrusion

As our target reaction scale of ca. 100 g would require large and cumbersome reactor vessels, we switched from batch synthesis to a continuous manufacturing methodology based on twin-screw extrusion (TSE) procedure. Notably, TSE was recently described in continuous- and solvent-free synthesis of four other commercially interesting MOFs.⁵ The procedure is based on use of a twin-screw laboratory extruder (Figure 3a), wherein the reaction mixture, added continuously through the feeder, is milled and transported along two co-rotating screws before exiting the instrument. In our case we have used Rondol 21mm LAB TWIN extruder where the

die at the end of the tube was removed in order to avoid clogging by product particles. To be able to use this equipment on larger scale, the main prerequisite is the accessibility of a large quantity of starting compounds. Whereas the 2-aminoterephthalic acid linker is commercially available, compound **1** was synthesized readily on 100 g scale, simply by mixing of a solution of zirconium propoxide with acetic acid (Experimental section). Colorless crystals can be isolated and filtered after a day or two of standing on room temperature. We premixed **1** and 2-aminoterephthalic acid in a large glass beaker before starting to add it carefully through feeder, and MeOH was added through the adjacent inlet to provide necessary lubrication and to catalyze the reaction. We have chosen MeOH rather than water, used in milling procedures involving mixer or planetary mills, as mixtures in liquid-assisted grinding with methanol additive seemed to flow more readily through the extrusion reactor.

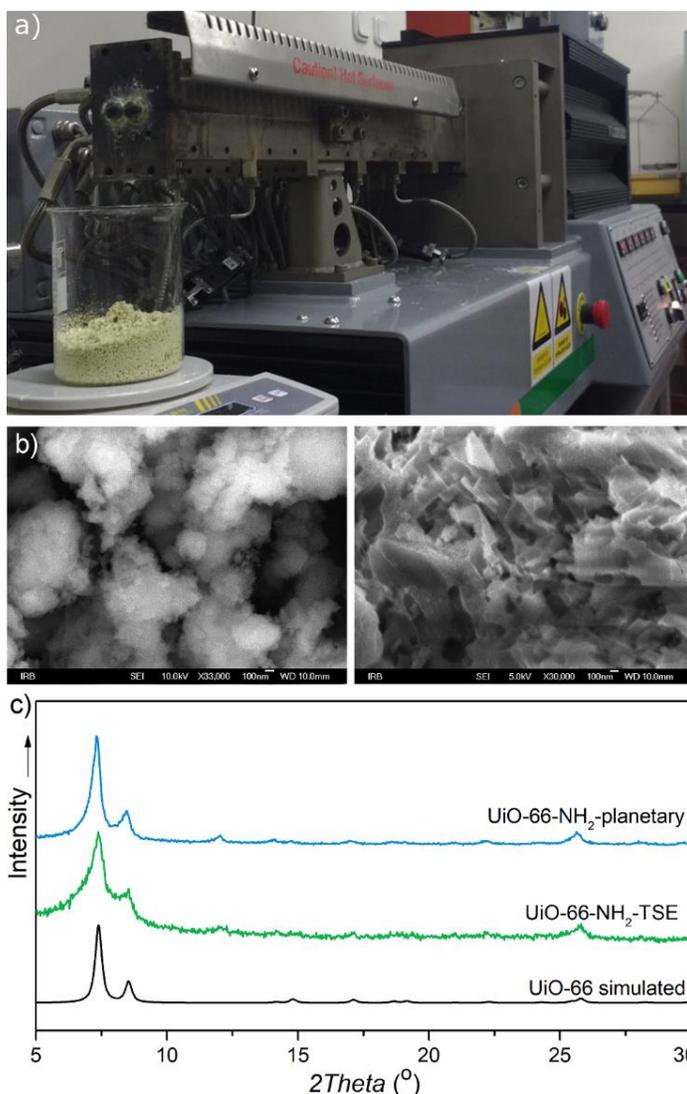


Figure 3. a) The TSE setup used for continuous mechanochemical synthesis of UiO-66-NH₂. Extruded UiO-66-NH₂ was collected in 1 L beaker; b) SEM micrographs of UiO-66-NH₂ prepared by TSE (left) and by milling in planetary mill (right); and c) PXRD patterns of UiO-66-NH₂ obtained on 10 g scale in planetary mill and on 100 g scale by continuous mechanochemical procedure using TSE.

The product after the first pass was pale yellow in color, consistent with the color expected of UiO-66-NH₂. In accordance with standard TSE procedure, the obtained mixture was fed through

extruder one more time to ensure larger residence times, and consequentially, a higher yield of the product. At the screw speed of 180 rpm, the accomplished throughput was around 23 g/min, equivalent to almost 1.4 kilograms of product per hour. The obtained pale-yellow powder was washed with small volume of MeOH and identified as UiO-66-NH₂ using PXRD analysis (Fig 3c). The particles in the sample are smaller than 100 nm in diameter and agglomerate to loosely bound spheres, similar to UiO-66-NH₂ obtained on 200 milligram scale by LAG procedure using laboratory mixer mill (Figure 3b, left).

Porosity measurements

In addition to confirming crystallinity and topology, it is important to determine how the proposed mechanochemical procedures affect the MOF porosity. Zirconium MOFs are generally considered to be highly stable in aqueous environments, which is a basis for their potential application in remediation of chemical warfare agents and other pollutants. The surface area of UiO-66, UiO-66-NH₂, MOF-801, MOF-804 samples prepared by LAG with water and activated by a standard procedure, shows that the proposed laboratory mechanochemical LAG procedure did not influence significantly on the porosity of prepared materials (Figure 4). The measured Brunauer-Emmett-Teller (BET) areas for samples of UiO-66, UiO-66-NH₂, MOF-801 and MOF-804 were 1145, 815, 540 and 755 m² g⁻¹, respectively (Table 1 and Figure 4). These results are consistent with the literature values for analogous materials synthesized solvothermally⁶⁹ or by mechanochemical batch synthesis using LAG in the presence of MeOH additive.⁹ The hysteresis observed in isotherm of the UiO-66 sample is most likely due to small particles (<100 nm diameter) which are compacted strongly (Figure 2a), thus creating inter-particle voids that may act like larger mesopores. UiO-66-NH₂ prepared in a planetary mill on 10 g scale with water additive

displayed excellent BET surface area (885 m²/g), while the sample made on 100 g scale by TSE showed somewhat lower surface area (610 m²/g).

Importantly, the latter two samples were activated using a much simpler procedure than conventionally used for MOFs and applied for other tested samples (Experimental section). As these samples were synthesized in the presence of small amounts of water or alcohols, we aimed to avoid the conventional solvent-exchange procedure which is inherently wasteful, involves multiple washing with the volatile and hazardous organic solvents, and requires specialized equipment. In the herein developed procedure, the MOFs were simply kept overnight in vacuum at 120 °C, leading to excellent BET surface areas. Consequently, the herein developed green and environmentally-friendly synthetic procedures also enable a cleaner, more materials-efficient activation of the MOF products.

Table 1. BET surface areas of mechanochemically prepared UiO-MOFs (in m²/g), determined from N₂ sorption measurements at 77 K.

MOF	Additive H ₂ O	Additive MeOH	Literature ^{a 69}
MOF-801	540	-	690 (SC ^b), 990 (P ^b) ⁷²
MOF-804	755	-	560 ⁶⁹
UiO-66	1145	1020 ⁹	1100 ⁶⁹
UiO-66-NH ₂	815	945 ⁹	830 ⁶⁹
UiO-66-NH ₂ (planetary) ^c	885		
UiO-66-NH ₂ (TSE) ^c		610	

a – Solvothermally obtained MOFs.

b - SC: Single Crystal; P: Powder.

c – Materials were activated without the solvent exchange, by heating the samples to 120 °C in a lowered pressure atmosphere.

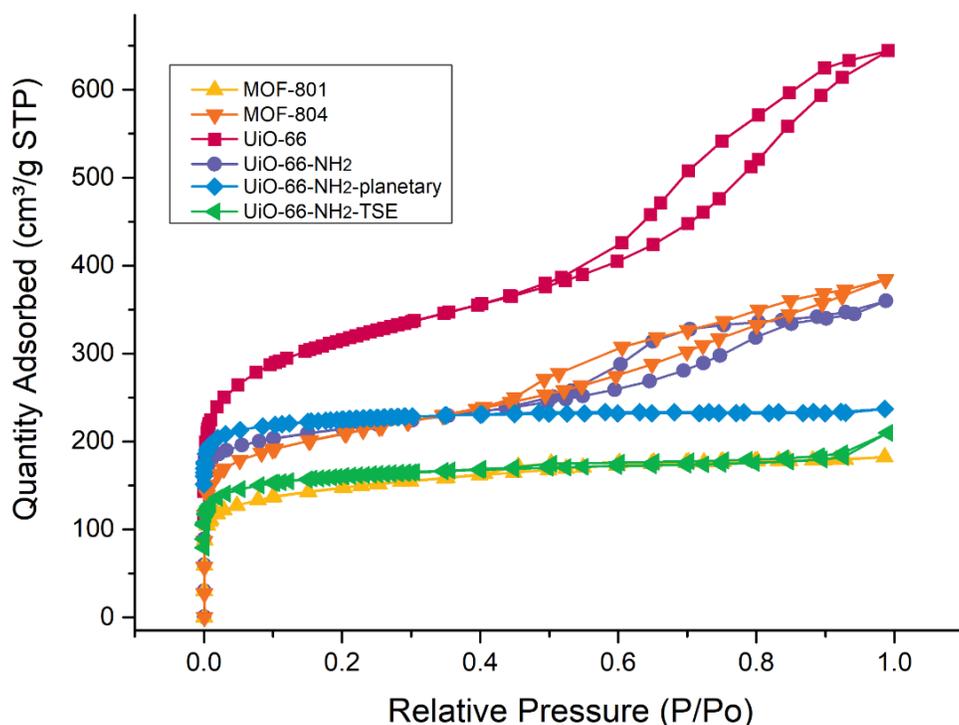


Figure 4. Nitrogen adsorption-desorption isotherms measured at 77K for Zr-MOFs prepared by mechanochemical procedures from **1**.

Catalytic activity

After confirming the permanent porosity and phase purity of the mechanochemically produced UiO-type MOFs, we evaluated their applicability by assessing their activity as catalysts for hydrolysis of the nerve agent simulant dimethyl 4-nitrophenyl phosphate (DMNP, Figure 5). The mechanochemically prepared samples of UiO-66-NH₂, previously established to be one of the most potent catalysts for this reaction, expectedly displayed much higher catalytic activity ($t_{1/2}$ is ≈ 6 min for the UiO-66-NH₂ made by milling in IST-500 mixer mill) compared to UiO-66,

consistent with the previously described behavior of solvothermally prepared UiOs.⁷³ Interestingly, UiO-66-NH₂ prepared by TSE on a 100 g scale showed the best catalytic activity among all tested samples ($t_{1/2}$ is ≈ 5 min), which is possibly due to the good dispersibility of the loosely bound particles (Figure 3b) in water. The UiO-66-NH₂ sample obtained from the planetary mill formed large agglomerates in the solid-state (please check Supporting Information) and the solution, which would not disperse despite the long sonication, and that was the only tested UiO-66-NH₂ sample that showed moderate hydrolytic activity under these experimental conditions. It is worth noting that the overall catalytic activity reported here is slightly lower compared to solvothermally prepared UiO-66-NH₂ due to the formation of larger agglomerates, resulting in limited dispersibility in water.

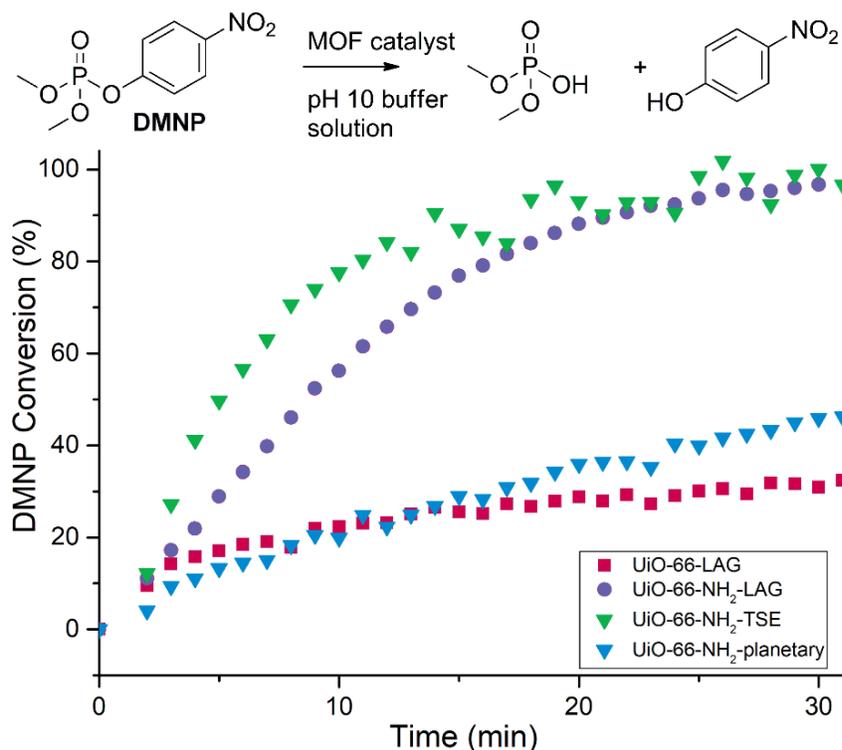


Figure 5. Comparison of hydrolysis profiles for a degradation of nerve simulant DMNP in the presence of UiO-66 (red – prepared by LAG in IST-500 mixer mill) and UiO-66-NH₂ (purple –

sample from batch LAG in IST-500 mill; green – sample prepared by TSE; and blue – sample prepared by milling in planetary Fritsch Pulverisette 6 mill).

CONCLUSIONS

In summary, we have developed a rapid, scalable and green mechanochemical synthesis of a series of Zr_6 -based MOFs with *fcu* topology (UiO-66, UiO-66-NH₂, MOF-801 and MOF-804) *via* water-assisted grinding. The procedure relies on use of a Zr_{12} acetate precursor and a minute amount of liquid additive to afford high-quality *fcu*- Zr_6 MOFs in a batch- or flow mechanochemical reactors, with minimum work-up needed and with acetic acid as an exclusive by-product. Reactivity of the Zr_{12} acetate cluster proved superior to reactivity of the more commonly used Zr_6 methacrylate cluster, which was successful for MOF-801 synthesis only. The proposed mechanochemical procedure can be scaled to 10-gram scale using a planetary mill, or even to larger scales using continuous processing by twin-screw extrusion, affording >100 g of UiO-66-NH₂ MOF at a rate of ca. 1.4 kg/h. The obtained products showed high crystallinity and porosity without the need for excessive work-up or the stabilization of the framework by DMF. For materials prepared on a larger scale, simple thermal activation without long and costly solvent-exchange procedures was sufficient to yield activated MOFs with high BET surfaces. The catalytic activity of UiO-66-NH₂ and UiO-66 prepared from the acetate precursor by water-assisted mechanochemistry was comparable to their conventionally-prepared counterparts. Based on these encouraging results, we believe this Zr_{12} acetate cluster may become a common precursor in development of greener and safer synthetic procedures for other commercially interesting zirconium MOFs.

EXPERIMENTAL SECTION

Zr(IV) propoxide (70 % wt. in 1-propanol solution) was obtained from Sigma Aldrich, acetic acid (99.5% purity) was obtained from Kemika, terephthalic acid (tpa) was obtained from Merck, 2-aminoterephthalic acid (atpa) and fumaric acid (fum) were obtained from TCI, and 2,5-dihydroxyterephthalic acid (dhta) (97% purity) was obtained from Alfa Aesar. All reagents were used without further purification, and all reactions were conducted with deionised water. Cluster 2 ($\text{Zr}_6\text{O}_4(\text{OH})_4(\text{C}_2\text{H}_3\text{CO}_2)_{12}$) was prepared according to the literature.⁷¹

Synthesis of acetate cluster $[\text{Zr}_6\text{O}_4(\text{OH})_4(\text{CH}_3\text{COO})_{12}]_2$ (1). Synthesis of 1 was conducted according to the literature method.⁷⁴ Zirconium(IV) propoxide (% 70 wt. % 1-propanol solution) (1g, 3.05 mmol) and acetic acid (3.50 mL) (1:20 ratio) were mixed in a sealed beaker and left overnight at room temperature. Microcrystalline colourless powder was collected by filter suction, washed with acetic acid gently and dried at room temperature. Yield: 0.825 g, 95 % based on zirconium(IV) propoxide.

Attempted water-assisted LAG synthesis of UiO-66, UiO-66-NH₂, MOF-801 and MOF-804 using methacrylate cluster 2. The methacrylate-based cluster 2 (0.052 mmol), organic linkers (terephthalic acid, 2-aminoterephthalic acid, 2,5-dihydroxy terephthalic acid and fumaric acid) (0.315 mmol) (1:6 molar ratio of cluster 2 to organic linker) and 50 μL H₂O were placed into a Teflon jar equipped with two stainless steel balls (1.38 g each) and milled for 90 minutes using IST-500 mixer mill operating at 25 Hz. Resulting powders for each reaction were washed with water or MeOH and analysed by PXRD and FTIR-ATR.

Water-assisted milling synthesis of UiO-66-NH₂ from 1. Optimised LAG assisted milling reaction of UiO-66-NH₂ was performed at IST-500 mixer mill at 25 Hz for 90 min. Zr₁₂ precursor (64.8 mg, 0.023 mmol), 2-aminoterephthalic acid (50.77 mg, 0.28 mmol) (molar ratio of 1:12) and 50 μ L H₂O were placed into a Teflon jar (10 mL) with two stainless steel balls (1.38 g each). The resulting yellow powder was washed with water or MeOH and analysed by PXRD, FTIR-ATR and TGA. Isolated: 111 mg.

Water-assisted milling synthesis of MOF-801 from 1.

Compound 1 (89.5 mg, 0.0263 mmol), fumaric acid (36.66 mg, 0.315 mmol) and 50 μ L H₂O were placed into a plastic jar (10 mL) with two stainless steel balls (1.38 g each). The reaction mixture was milled using IST-500 mixer mill at 25 Hz for 90 min. The resulting white powder was washed with water or MeOH and analysed by PXRD, FTIR-ATR and TGA. Isolated: 87 mg.

Water-assisted milling synthesis of MOF-804 from 1.

Compound 1 (89.5 mg, 0.0263 mmol), 2,5-dihydroxyterephthalic acid (62.58 mg, 0.315 mmol) and 50 μ L H₂O were placed into a plastic jar (10 mL) with two stainless steel balls (1.38 g each). The reaction mixture was milled using IST-500 mixer mill at 25 Hz for 90 min. The resulting yellow powder was washed with water or MeOH and analyzed by PXRD, FTIR-ATR and TGA. Isolated: 108 mg.

Two-step water-assisted milling synthesis of UiO-66 from 1.

UiO-66 was synthesised in two reaction step. First, terephthalic acid (52.47 mg, 0.315 mmol), triethylamine (63.80 mg, 0.631 mmol) and 50 μ L H₂O were placed into a Teflon jar (10 mL) and milled for 30 min at 25 Hz using two stainless steel balls (1.38 g each) and InSolido Technologies IST-500 mixer mill. Zr₁₂ precursor 1 (89.5 mg, 0.0263 mmol) was added afterwards to this mixture and stirred for additional 90 min. The resulting white powder (isolated 95 mg) was washed with methanol (MeOH), dried in air and analysed by PXRD, FTIR-ATR and TGA.

10-gram scale mechanochemical synthesis of UiO-66-NH₂ in a planetary mill.

Gram-scale mechanochemical synthesis of UiO-66-NH₂ was conducted using a Fritsch Pulverisette 6 planetary mill operating at 500 rpm. 7.16 g of compound **1** was mixed with 4.58 g of 2-aminoterephthalic acid in a 50 mL reaction vessel made of ZrO₂ with three ZrO₂ balls (each weighing 3 g), followed by the addition of 4 mL of water. After 90 minutes milling, pale-yellow product was isolated and washed three times with small volume of methanol. Isolated: 11.3 g of UiO-66-NH₂.

Continuous mechanosynthesis of UiO-66-NH₂ by TSE.

Continuous mechanochemical synthesis experiment was carried out in Rondol 21mm LAB TWIN co-rotating, intermeshing twin screw extruder (TSE), shown in Figure 3a. Total barrel length was 630 mm, leading to L/D ratio of 30. Apart from forward-conveying sections, screws were equipped with three kneading blocks comprising 5mm wide bi-lobed elements arranged in 30, 60 and 90° stagger angles with lengths of 65, 25 and 50 mm respectively. Barrel of the extruder consisted of five individual heating/cooling sections (Figure 3a). Barrel was kept at 40°C to ensure smooth screw rotation. For the purpose of this experiment, die at the end of the extruder barrel was

removed and the extruded material was collected in a weighed beaker. Reactants were gently premixed in a beaker and fed manually through the first feed port. Screw speed was kept at 180 rpm, at which torque was kept at 90 % of maximum value, providing as high as possible throughput for current screw configuration. To facilitate longer residence times and ensure higher conversion, obtained product was fed through extruder one more time. Isolated: 104 g of UiO-66-NH₂.

Activation and porosity measurements

Samples were shipped to Northwestern University as wet powders containing a minimal amount of H₂O or methanol. Nitrogen adsorption and desorption isotherm measurements were performed on a Micromeritics Tristar II at 77K. All gases used were Ultra High Purity Grade 5 gases from Airgas Specialty Gases. Prior to measuring the nitrogen adsorption-desorption isotherms, the materials obtained by milling in mixer mill were activated as following: each sample (~60 mg each) was then soaked in 12 mL of acetone in a 15 mL polypropylene centrifuge tube. After soaking for 3 hours, the MOF sample was centrifuged and the acetone was removed using a Pasteur pipette. 12 mL of fresh acetone was then added to the MOF sample in the 15 mL polypropylene centrifuge tube. The sample was allowed to soak in the fresh acetone for 3 hours before repeating centrifugation and removal of solvent. Finally, 12 mL of fresh acetone was added to the MOF sample in the 15 mL polypropylene centrifuge tube and allowed to soak for 18 hours before repeating centrifugation and removal of solvent. The sample was then placed in a vacuum oven set at 80 °C for 6 hours to remove the majority of the acetone in the sample. Lastly, the MOF was thermally activated under ultra-high vacuum at 120 °C for 18 h on a Micromeritics Smart VacPrep instrument.

A bit milder technique using supercritical CO₂ drying was performed for activation of UiO-66 sample using a Tousimis™ Samdri® PVT-30 critical point dryer (Tousimis, Rockville, MD, USA). Supercritically dried samples were prepared in the following manner. The solvent is exchanged with absolute ethanol overnight. The ethanol-dispersed sample was transferred into the sample holder with a glass pipet and allow for settling down overnight. The next day, excess of EtOH was pipetted out and the sample holder was placed into a Tousimis Samdri-PVT-3D supercritical CO₂ dryer. The temperature was lowered to 0 °C, and the chamber was filled with liquid CO₂ (ultrahigh grade CO₂ with a syphon from Air-Gas Inc was used). The sample was soaked for 8 hours total, with five minutes venting for every two hours. The chamber was then heated to 40 °C, and the supercritical CO₂ was bled off at a rate of 0.5 mL/min until the chamber reached close-to-ambient pressure. The chamber was opened and the sample was quickly transferred into a pre-weighed glass sample tube which was sealed and quickly transferred to a system providing 10⁻⁴ torr dynamic vacuum. The sample was kept under vacuum at 50 °C for 2 hours and was then used for N₂ adsorption measurements using Micromeritics Tristar II at 77K.

For the MOF samples prepared by TSE or planetary mill even simpler activation procedure was used. The materials were, without the solvent exchange or supercritical CO₂ treatment, subjected to thermal activation under vacuum at 120 °C for 16 hours before the N₂ adsorption measurements on a Micromeritics Tristar II at 77K were conducted.

Catalytic activity measurements

Hydrolysis profiles were recorded by in situ ³¹P NMR spectroscopy at room temperature. MOF catalyst 1.5 μmol (2.5 mg of UiO66; 3.2 mg of UiO-67 (corresponds to 6 mol% catalyst (Zr₆ node)) weighted using a microbalance and transferred into a 1.5 dram (≈5.5. mL) vial and 0.4 M N-

ethylmorpholine solution (1.05 mL; 0.05 mL N-ethylmorpholine, 0.9 mL deionized water and 0.1 mL D₂O) was added and then sonicated for 30 seconds to disperse homogeneously. DMNP (4 µL; 25 µmol) was added to mixture solution and swirled for 15 seconds. The reaction mixture was then transferred to an NMR tube and the spectrum was immediately measured; the first data point was collected 120 seconds after the start of the reaction. The progress of the reaction was monitored with 1 min increments (number of scans = 16, delay time = 28 sec).

ASSOCIATED CONTENT

Supporting Information.

Powder X-ray diffraction (PXRD) analysis, thermogravimetric analysis (TGA/DTA), and FTIR-ATR analysis.

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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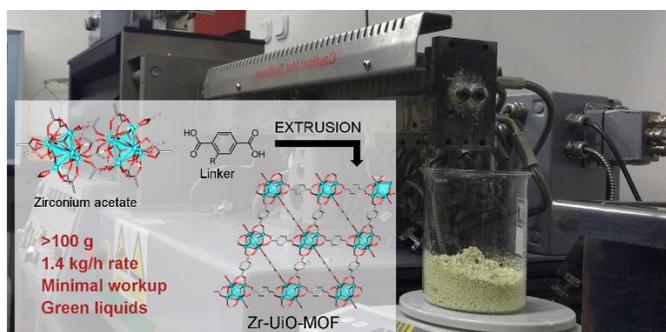
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TOC Graphics

TOC Graphics and Synopsis



The use of a zirconium dodecanuclear acetate cluster enabled fast and large-scale production of UiO-MOFs by water-assisted mechanochemistry or twin-screw extrusion.