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PERSPECTIVE

De facto methodologies toward the synthesis and scale-up production of UiO-66-type metal-organic frameworks and membrane materials

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Metal-organic frameworks (MOFs) are architected via coordination bonds between inorganic metal nodes and organic ligands. They have become emerging advanced porous materials and gained ever-increasing attention in the past decade. In particular, overwhelming studies have been devoted to those hydrostable MOFs which are suggested to be highly promising for industrial applications. UiO-66 is such a unique MOF because of its superior thermal/chemical stability and structural tunability. However, its repeatable, green, and scale-up synthesis remain a challenge for its commercialization and implementation in industrial applications. This perspective mainly summaries the recent development in the synthesis of UiO-66-type MOFs and their related composites. From a scale-up viewpoint, we also present some important advances in batch and continuous reactor synthesis toward their massive production (226 references).

1. Introduction

Metal-organic frameworks (MOFs), architected via coordination bonds between inorganic metals and organic ligands, have become emerging advanced porous materials and gained ever-increasing attention recently.[1-3] Until now, more than 100,000 MOFs[3] with different constituent, pore geometry, pore size, and functionality have been reported, largely because of the availability of various metal nodes, organic ligands, and rich coordination modes.[4] So far, major investigations have been devoted to the synthesis and possible applications of new MOFs, and several critical reviews have already addressed their synthesis,[4-11] structure design,[12-20] and applications.[3, 21-23] However, a big challenge is that most of the reported MOFs suffer from critical problems of inherently weak hydrothermal and chemical stabilities that prevent their industrial applications.[24, 25] Luckily, there are still several types of MOFs that have been identified as robust and moisture-resistant, such as MILs,[26-28] Zr-MOFs,[29-34] ZIFs,[35-37] pyrazolate-bridged MOFs,[38] F-containing MOFs,[39, 40] Al and Fe MOFs,[41, 42] PDMS coated MOFs,[43] etc. Among these MOFs, UiO-66[29] and UiO-66-type MOFs have been recently identified to own superior chemical and hydrothermal stability.[30, 44, 45] Since its discovery in 2008, UiO-66 has been widely investigated in the areas of isostructural synthesis, synthetic method, and potential application. The importance can be readily seen from the large number of studies. Until now, more than 300 relevant publications have been devoted to disclosing the synthetic methodologies, post-modifications, and potential applications of this MOF.[46] This is probably because of its mild synthetic conditions that make it easy to be repeated and functionalized for various applications.

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This perspective will mainly focus on addressing the synthetic approaches and post-synthetic modifications of UiO-66-type MOFs whereas their applications will not be fully covered herein. Firstly, we will delineate the constructing units, ligands, and crystal structures of pristine UiO-66. Secondly, we will discuss the basic solvothermal synthesis of UiO-66 and factors that play major roles. Thirdly, we will introduce the recently developed scale-up methods and post-synthetic approaches devoted to developing, optimizing, and functionalizing UiO-66-type MOFs, especially those new approaches toward the green, repeatable, and scalable synthesis. UiO-66-containing membrane materials will also be discussed due to their important applications in separation. After that, we will briefly discuss a new research field regarding the defects in UiO-66. Last but not least, we will highlight the challenges and possible trends in the future development of UiO-66-type MOFs.

2. Briefing of UiO-66-type MOFs

UiO-66 (Zr) is composed of zirconium (Zr) clusters as secondary building units (SBUs) and BDC (1, 4-benzenedicarboxylic acid) as the linkers.[29, 47, 48] Belonging to the same IV group, titanium (Ti) and hafnium (Hf) should also be able to form isostructural UiO-66 MOFs. However, Ti-BDC MOF has been reported as MIL-125 instead of UiO-66-type.[49, 50] In 2012, UiO-66 with Hf as the metal nodes was synthesized and identified.[47] Since Hf-MOFs possibly own stronger Brønsted acid sites than Zr-MOFs,[51, 52] several attempts have been devoted to the synthesis of Hf-MOFs.[53-57] Recently, cerium (Ce).[58] uranium(IV, U),[59 60] thorium (Th),[61] have been also reported capable of forming UiO-66-type structure via a solvothermal approach. The UiO-66(Ce) and UiO-66(Th) showed good surface area (Table 1) but UiO-66(U) is quite fragile and usually collapses during activation process. Due to the limited reports and requirement of further demonstration of potential applications, they will not be covered in detail in the following sections. In view of the fact that traditional solvothermal synthesis containing Hf or Ti usually ends up with either amorphous solids or viscous gels,[6] the synthesis of UiO-66(Hf/Ti)-type MOFs remains challenging. Therefore, the development of new synthetic approaches is especially desired for disclosing their structural properties and potential applications.

Fig. 1 lists all the commercially available or synthetically feasible BDC-type ligands. The first two ligands are not BDC-type but linear similar to BDC-type ligands, and their according MOFs have been recently reported.[31, 62] The rest ligands are all with the similar structure but different functionalities indicating different reactivity and coordination capability. In addition, other bidentate ligands, such as 4, 4'-biphenyl-dicarboxylate (BPDC), terphenyl dicarboxylate (TPDC), etc., can also form similar but extended structures, called UiO-67 and UiO-68.[29] The discussion of these MOFs is beyond the scope of this perspective.

UiO-66(Zr) contains SBUs of $Zr_6O_4(OH)_4$ cluster (Fig. 1a) in which the triangular faces of the Zr_6-octahedron are alternatively covered by μ_3-O and μ_3-OH groups.[29, 63] Furthermore, all of the octahedron edges are bridged by carboxylates from BDC ligands (Fig. 1b) to form the overall crystal structure (Fig. 1c). It has a coordination number of 12 which is among the highest of all the reported MOFs so far.[29] This high degree of network connection is believed to account for its exceptional stability.[64] In the literature, the framework structure can often be simplified as an octahedron to clearly indicate the chemical structure of ligands (Fig. 1d).

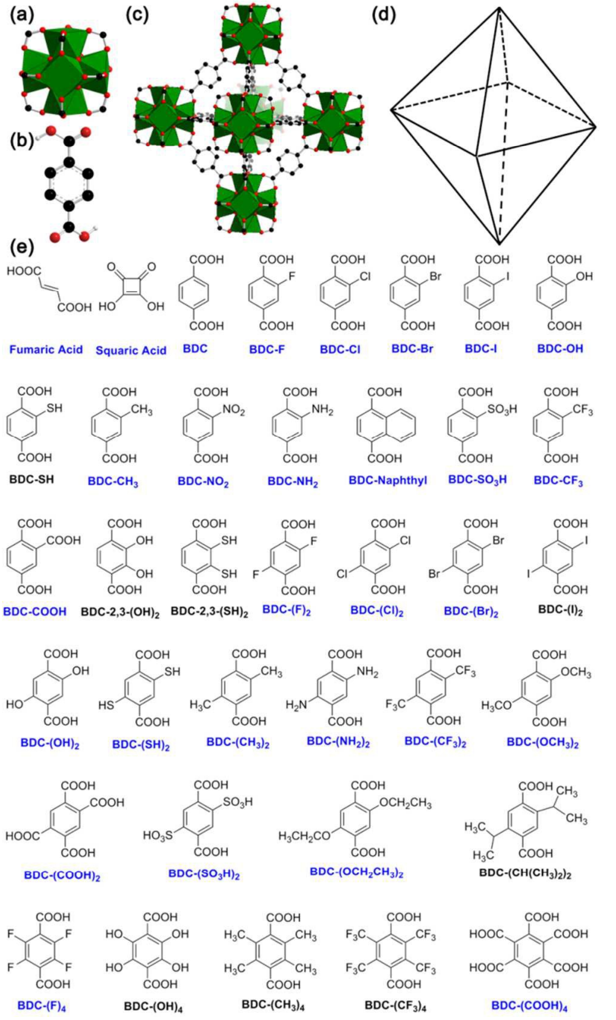

Fig. 1 Illustration of UiO-66: (a) secondary building units (SBUs); (b) BDC ligand; (c) crystal model; (d) a simplified form; (e) commercially available or synthetically feasible BDC-type ligands. Ligands labeled as blue indicate their according MOFs have been attempted.

Table 1 summarizes several representative recipes and surface areas for solvothermally synthesized pristine UiO-66 (Zr or Hf). The calculated theoretical surface areas for pristine UiO-66(Zr) and UiO-66(Hf) are 1550 m^2 g^{-1} and 1050 m^2 g^{-1}, respectively.[65] We have recently obtained the highest BET surface area of UiO-66(Zr) (1730 m^2 g^{-1}) synthesized using 100 equivalent formic acid as the modulator.[66] For UiO-66(Hf), although several papers have reported its synthesis, the crystallinity and surface area remain to be further optimized.[47, 67] The highest BET surface area of UiO-66(Hf) reported in the literature is 750 m^2 g^{-1},[67] lower than that of UiO-66(Zr). However, we have recently applied modulated hydrothermal method to synthesize UiO-66(Hf)-NH_2 with a much higher BET surface area of 1067 m^2 g^{-1} (*vide infra*).[68] Table 2 summarizes gas sorption properties of all the reported UiO-66-type MOFs up to now. Their CO_2 separation performance is also included because these MOFs have been widely attempted for CO_2-related gas separations.[69]

3. Solvothermal synthesis

3.1 The state of the art progress

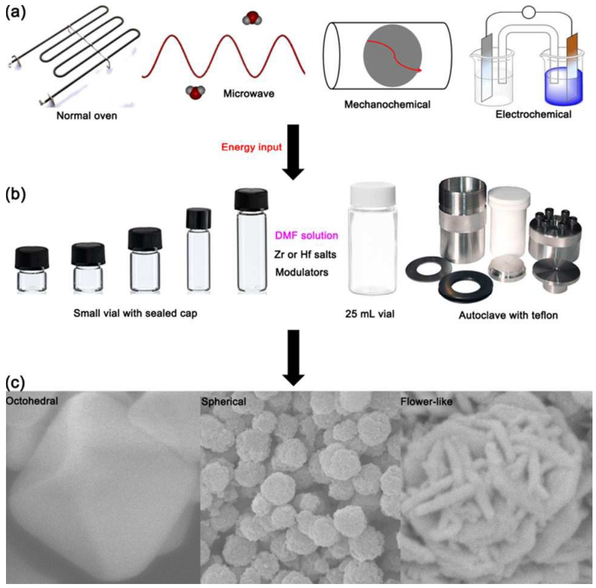

Fig. 2 Scheme of solvothermal synthesis: (a) energy sources; (b) apparatus; (c) morphologies of MOF products.

Solvothermal synthesis is a typical method to grow crystals from solutions in autoclaves or glass vials under high temperature and autogenous pressure.[6, 70-72] Fig. 2 shows the typical energy input and apparatus set-up for solvothermal synthesis. As is often seen in the literature, ohmic heating dominates the energy input while other kinds of energy forms, such as microwave heating, mechanochemical energy, electrochemical energy, etc., are good supplements for a faster and scalable synthesis.[73] The synthesis can be carried out either in glass vials or Teflon-lined autoclaves depending on the scale and experimental conditions. The solvothermally synthesized UiO-66 usually takes the form of small spherical nanoparticles (200~500 nm, Fig. 2c) while modulators, such as formic acid, are usually required in order to obtain crystalline products with well-defined octahedral shape (Fig. 2c).[62, 74, 75] Given the amphiphilicity of some ligands, the MOF products sometimes exhibit other interesting morphologies such as flower, rod, etc.[76-78]

3.2 Factors influencing synthesis of UiO-66

In order to successfully synthesize MOFs with high crystallinity and surface area, we have to understand the underlying dominant factors, which could possibly influence the homogeneity of the system and reaction kinetics. There are many factors (Fig. 3) that may influence solvothermal synthesis, such as solvent type, temperature, modulators, addition order, apparatus set-up, etc. Temperature is among the initial several factors that need to be optimized for better MOF products.[79] For UiO-66-type MOFs, 120 °C is most widely applied while in some cases 135 °C,[80] 150 °C,[81] and 220 °C[82] are adopted. When it comes to water-based synthesis, 100 °C is a dominant and energy-saving option wherein the whole system will be under reflux at 1 atm. In rare cases, 80 °C is applied possibly because some functional ligands, such as sodium 2-sulfoterephthalate, may exhibit amphiphilicity boosting the coordination reactions.[76] As for solvent, dimethylformamide (DMF) and water are most frequently used for solvothermal and hydrothermal synthesis, respectively. In some cases diethylformamide (DEF)[80] and N, N'-dimethylacetamide (DMA)[81] were also applied. Another factor is modulator, which can play an important role in synthesizing UiO-66-type MOFs.[74] Recently, researchers have expanded the scope of modulator into trifluoroacetic acid (TFA), hydrochloride acid (HCl), formic acid (FA), or even water for the solvothermal synthesis of UiO-66-type MOFs hoping to get better crystallinity and surface area.[65, 83-87] For example, Farha and his co-workers used HCl as the modulator and obtained a UiO-66 with a high BET surface area of 1580 m^2 g^{-1},[65] almost doubled compared with that of the original one (800-900 m^2 g^{-1}).[29] Another exciting example is done by our group. We have used formic acid and successfully obtained a hierarchical porous UiO-66 with a BET surface area of 1730 m^2 g^{-1} and a mesopore of 3.9 nm just as mentioned above.[66]

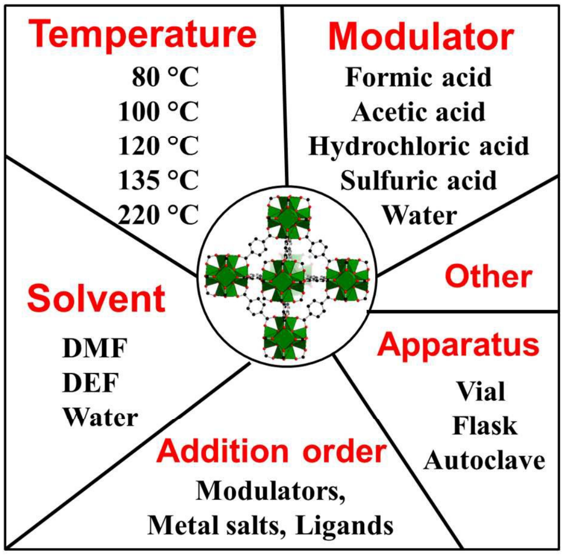

Fig. 3 Factors influencing the solvothermal synthesis of UiO-66-type MOFs.

Table 1. Representative recipes for solvothermal synthesis of UiO-66-type MOFs.

Items	UiO-66(Zr)[29]	UiO-66(Zr)[74]	UiO-66(Zr)[65]	UiO-66(Zr)[86]	UiO-66(Zr)[66]	UiO-66(Hf)[47]	UiO-66(Hf)[67]
Metal salts (mg/mmol)	$ZrCl_4$ (53/0.227)	$ZrCl_4$ (57/0.3)	$ZrCl_4$ (125/0.54)	$ZrCl_4$ (51300/220)	$ZrCl_4$ (116/0.5)	$HfCl_4$ (150/0.47)	$HfCl_4$ (960/3)
Ligand amount (mg/mmol)	BDC (37/0.227)	BDC (80/0.3)	BDC (123/0.75)	BDC (35600/220)	BDC (83/0.5)	BDC (87/0.52)	BDC (498/3)
Modulators	N.A.	Acetic acid (0.5 mL)	HCl (1 mL)	Formic acid (829 mL)	Formic acid (1.89 mL)	H_2O (0.01 mL)	Formic acid (20 mL)
DMF (mL)	26	20	15	2000	18	5	40
Modulator/Ligand molar ratio	N.A.	30	15.5	100	100	1.06	177
Temperature (K)	393	393	353	393	393	373	393
Time (h)	24	24	12	24	24	24	24
Product types	Cubic (~100 nm)	Octahedral (~200 nm)	Spherical (~200 nm)	Octahedral (~3 μm)	Octahedral (~300 nm)	Spherical	Irregular (~500 nm)
BET/Langmuir surface area (m^2 g^{-1})	N.A./1187	1400/N.A.	1580/N.A.	1367/N.A.	1730/2047	655/N.A.	750/N.A.

Table 2. Gas sorption properties of representative UiO-66-type MOFs.

UiO-66-type MOFs	BET SA[a)]	Langmuir SA[a)]	Pore volume[b)]	CO_2 uptake, 298 K		Q_{st} of CO_2[d)]	IAST CO_2/N_2 selectivity[e)]
				0.15 bar[c)]	1 bar[c)]		
ZrFMA[62, 88, 89]	856/809[31]		0.34[31]		1.82[90]		
ZrSQU[31]	179						
UiO-66(Zr)[91]	1525/1290[30]	1757	0.66	0.37	1.79	26.5[92]/26.2[93]/24.5	19.4
UiO-66(Zr), optimized[66]	1730	2047	0.80	0.56	2.20	23.3	19.1
UiO-66(Zr)-NH_2[94]	1123	1250[95]	0.52	1.11	~2.80	~28.0/28.6[93]	32.3
UiO-66(Zr)-OH[65]	1000/946[96]						
UiO-66(Zr)-F[97]		919	0.26				
UiO-66(Zr)-Cl[98]	430	766[97]	0.25[97]/0.23				
UiO-66(Zr)-Br[99]	801/640[98]	899[95]/886		~0.75	~2.90	~24.0/28.4[93]	

UiO-66(Zr)-I[81]	799		0.27				
UiO-66(Zr)-Naphthyl[94]	757	N.A.	0.42	0.41	~1.40	~25.8	22.2
UiO-66(Zr)-CH$_3$[98, 100]	760	856	0.34				
UiO-66(Zr)-NO$_2$[94]	869[99]/860[65] /792	980[99] /856[95]	0.40	0.58	~2.55	~32.5/30.9[93]	25.5
UiO-66(Zr)-(OCH$_3$)[97]		763	0.25				
UiO-66(Zr)-CF$_3$[97]		739	0.27			~34.1	
UiO-66(Zr)-COOH[81]	842		0.29			~33[93]	
UiO-66(Zr)-SO$_3$H[81]	769/339[101]		0.26			~33.8[93]	
UiO-66(Zr)-(F)$_2$[97]		836	0.28				
UiO-66(Zr)-(Cl)$_2$[97]		609	0.21				
UiO-66(Zr)-(Br)$_2$[97]		339	0.12				
UiO-66(Zr)-(OH)$_2$[102]	814[96]/755[98] /705	1011	1.08	0.65	1.95	30.1/ 29.4[93]	34.2
UiO-66(Zr)-(SH)$_2$[103]	308			~0.45	~1.10		
UiO-66(Zr)-(NH$_2$)$_2$[65]	540						
UiO-66(Zr)-(CH$_3$)$_2$[99, 104]	868	968		~1.30	~3.79	~38.0	~58
UiO-66(Zr)-(OCH$_3$)$_2$[94]	868	N.A.	0.38	0.89	~2.60	~31.5	29.8
UiO-66(Zr)-(CF$_3$)$_2$[93]	503[98]/334		~0.22			~34.1	
UiO-66(Zr)-(SO$_3$H)$_2$[103]	35			~0.22	~0.54		
UiO-66(Zr)-(COOH)$_2$[102]	494/441[105] /428[106]	608	0.29/0.26[106]	0.62	1.82	34.8[106]/33.6	35.4
UiO-66(Zr)-(OCH$_2$CH$_3$)$_2$[102]	405	575	0.41	0.18	0.65	26.2	24.9
UiO-66(Zr)-(F)$_4$[102]	833	1040	0.62	0.26	1.22	18.7	16.0
UiO-66(Zr)-(COOH)$_4$[102]	212	342	0.42	0.21	0.53	30.5	25.8
UiO-66(Hf)[47]	655	849					
UiO-66(Hf)-NH$_2$[68]	1067	1291	0.52	0.93	2.90	25.6	32
UiO-66(Hf)-(OH)$_2$[68]	922	1018	0.40	1.81	4.06	31.0	93
UiO-66(Hf)-(COOH)$_2$[68]	378	491	0.26	0.40	1.20	28.2	27
UiO-66(Hf)-(F)$_4$[68]	329	426	0.25	0.28	0.82	23.9	24
CeFMA[58]	732		0.30				
UiO-66(Ce)[58]	1282		0.50				
UiO-66(Ce)-F[58]	1075		0.42				
UiO-66(Ce)-CH$_3$[58]	985		0.39				
UiO-66(Ce)-Cl[58]	770		0.31				
UiO-66(Ce)-NO$_{23}$[58]	727		0.29				
UiO-66(U)[59]	7, collapsed						
UiO-66(Th)[61]	730	868	0.27				

a) m^2 g^{-1}; b) cm^3 g^{-1}, c) mmol g^{-1}, d) kJ mol^{-1}, e) CO$_2$:N$_2$ = 15:85, 298 K, 1 bar.

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Besides the species of chemical reagents, the order to add them is another important empirical factor for the successful synthesis of UiO-66-type MOFs. There are no general rules and the optimized adding order may vary from case to case. The reason is that different metal salts and ligands may have different reaction kinetics and coordination modes.[102] Last but not least, using different synthetic apparatus may provide different temperature, pressure, and reaction media for MOF growth. In general, the synthesis of UiO-66 is not only rational but also empirical, which requires both theoretical prediction and experimental confirmation.

3.3 Activation process of UiO-66-type MOFs

The yield of solvothermal synthesis varies from 30% to 60% and strongly depends on the purification process.[6, 107, 108] Therefore, the subsequent purification and activation process are of vital importance to obtain MOFs with high yield and surface area. In a typical process, the crude MOF product is firstly recovered by centrifuge and washed with solvent (e.g. DMF) to remove residual ligands trapped inside the framework.[91] After that, it is soaked in anhydrous volatile solvent (e.g. methanol) for an extended period of time (e.g. 3 days) to replace the non-volatile solvents used during synthesis with volatile one. Finally, the sample will be heated under vacuum to afford fully activated product for further characterization and application.

4. Advanced scale-up approaches

4.1 The art of "Cooking Hotchpotch"-Batch MHT synthesis

To develop a "universal approach" for the synthesis of UiO-66-type MOFs is exciting but also very challenging. Much work has been done toward this direction. For example, Maurin and his co-workers have reported pure water-based reflux synthesis of MOFs, such as UiO-66(Zr)-$(COOH)_2$,[106] MIL-53(Al)-FA,[109] etc. Inspired by this strategy, we have further developed it into a modulated hydrothermal (MHT) synthesis that can be used to synthesize UiO-66-type MOFs in a green, repeatable, and scalable way. We have found that by using acetic acid/water mixed solvent and zirconium nitrate as the metal salt, a series of UiO-66(Zr)-type MOFs can be facilely obtained with excellent crystallinity and gas uptake performance.[102] Our MHT synthesis is featured by three aspects: (1) metal salts and modulators are water-soluble while ligands are usually suspended in water, leading to heterogeneous reaction systems which might help to eliminate the "self-inhibition effect" from the ligands themselves; (2) water is used as an environmentally benign solvent; (3) controlled reaction kinetics through reversible reactions between solid ligand phase and aqueous solution phase mediated by modulators. Though the MHT synthesis, we have obtained some new UiO-66-type MOFs, such as UiO-66-$(F)_4$, UiO-66-$(OCH_2CH_3)_2$, etc., which cannot be directly synthesized through traditional solvothermal synthesis according to our initial experimental results. Meanwhile, we have also optimized the surface area and crystallinity of UiO-66-$(OH)_2$ and UiO-66-$(COOH)_2$.[102] In addition, we have recently proven that MHT can be used to synthesize new UiO-66(Hf)-type MOFs. This is in a sharp contrast with solvothermal reactions which usually result in gel-like glues or clear solutions.[68]

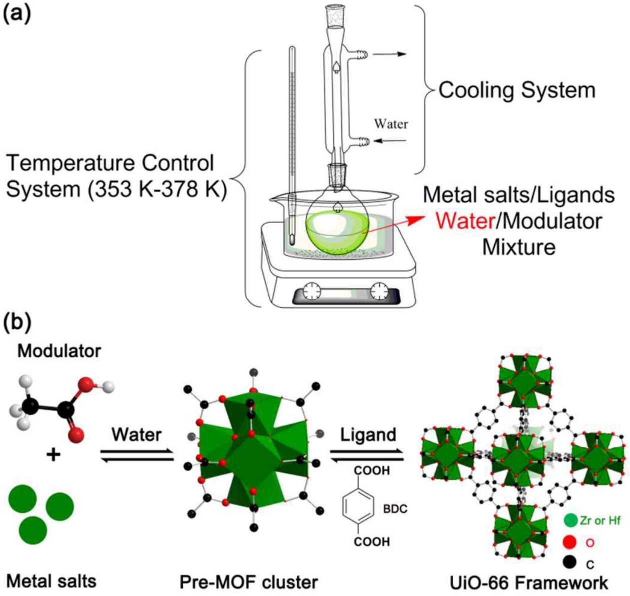

Fig. 4 Apparatus (a) and proposed mechanism (b) of modulated hydrothermal (MHT) approach for the synthesis of UiO-66-type MOFs.[102]

A simple reflux system often equipped in any synthetic labs can be used for the MHT synthesis (Fig. 4a). Based on our current understanding, the reaction may take place in two steps (Fig. 4b): metal salts initially react with modulators (both soluble in water) to form "pre-MOF" clusters,[110] followed by a reversible ligand exchange process to form extended frameworks. Experimental verification of this proposed mechanism is undertaking in our laboratory.

4.2 Continuous flow reactor synthesis

Compared to batch synthesis, the continuous synthesis of MOFs through flow reactors is more promising due to its faster heat and mass transfer leading to higher production throughput.[111] However, the precise control of mixing reagents can be quite challenging.[112-115] Walton *et al.* utilized a "countercurrent mixing reactor" and showed that countercurrent mixing at 300 °C could rapidly prepare HKUST-1 with excellent crystallinity and surface area comparable to the commercially available counterpart Basolite C300.[116, 117] Chang and his co-workers reported a solvothermal synthesis of HKUST-1 through a continuous-flow micro-reactor that can be finished within 5 min with a high yield.[118] However, the synthesis of UiO-66 via continuous flow reactors is more difficult because Zr salts are moisture sensitive leading to zirconia precipitation blocking the reaction pipes. Recently, Hill *et al.* reported a flow reactor synthesis of UiO-66(Zr) with a production rate of 60 g/h at extremely high space-time yields (Fig. 5).[119] This is an inspiring result which suggests a new realm of scale-up synthesis of UiO-66(Zr) MOFs. However, it needs to be pointed out that the surface area (1186 m^2 g^{-1}) and crystallinity of the UiO-66 product remain to be further optimized. More recently, Ahn *et al.* systematically conducted a pilot-scale (100 L) solvothermal synthesis of UiO-66 and achieved a BET surface area as high as 1387 m^2 g^{-1} and a high yield of 93%.[120] However, the usage of large amount of organic solvent (DMF) and high temperature largely increases the MOF production costs and remains the major challenge needs to be further resolved.

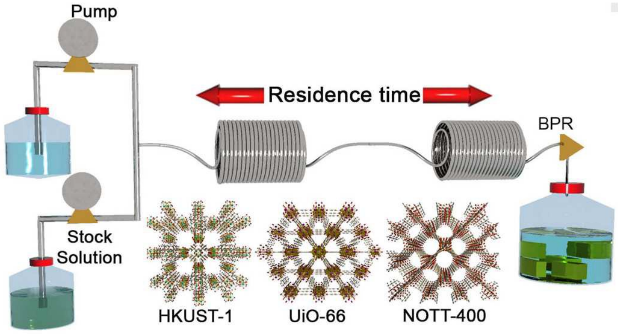

Fig. 5 A setup of flow reactor for the continuous production of MOFs.[119] Reprinted with permission from Nature Publishing Group Copyright 2014.

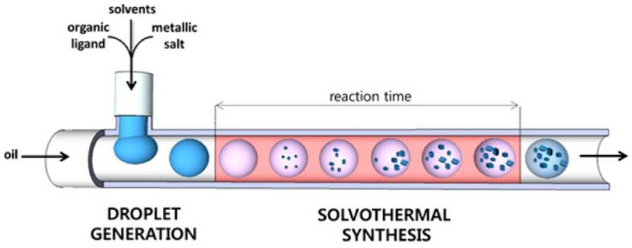

Fig. 6 Scheme of a microchemical process for ultrafast MOF synthesis.[121] Reprinted with permission from American Chemical Society Copyright 2013.

Microfluidic control, confining the reactants or target substrates within micro- or nano- liter droplets, is a newly emerging strategy to generate uniform emulsions in order to achieve exquisite control of crystallization or reaction processes.[122-124] Compared to conventional methods, microfluidic technologies could realize more precise control over the droplet size and uniformity of emulsions with better reaction kinetics and yield.[122-124] In 2011, De Vos *et al.* utilized this method to conduct an interfacial synthesis of HKUST-1 films and hollow capsules.[125] From then on, microfluidic devices have been increasingly applied for continuous synthesis of MOFs. For example, Kim *et al.* demonstrated a nanoliter droplet based microfluidic strategy for continuous and ultrafast synthesis of MOF crystals with core-shell heterostructures.[121] Representative experimental set-up is shown in Fig. 6. It has a biphasic system with a T-junction polydimethylsiloxane (PDMS) chip to generate droplets. Both organic ligands and metal salts are initially co-dissolved in a polar organic solvent, and then encapsulated in nanoliter droplets subsequently transported by the nonpolar silicon oil inside perfluoroalkoxyalkane (PFA) tubes. Finally, the whole PFA tube is heated in a silicon oil bath or an oven at a constant temperature (50−160 °C). The reaction time, which corresponds to the retention time, can be easily controlled by the flow rate or the length of tubes. Coronas and his co-workers also applied similar strategy and successfully obtained MIL-88b-type MOFs.[126] Although the microfluidic approach could provide an easy and fast synthesis of MOFs, the low throughput and compromised quality of the products are the major issues and how to conduct a precise control of the temperature, mixing, solvent evaporation, and to prevent droplet aggregation remain the key challenges.

5. Post-synthetic modification (PSM) of UiO-66-type MOFs

5.1 Sulfonation

One of the most prominent characteristics of MOFs is their tunability, especially the capability to incorporate active sites suitable for catalysis and other applications.[3] For example, coordinative unsaturated sites (CUSs) or unsaturated metal centers (UMCs) generated by removing solvent molecules from metal cluster SBUs have been reported to act as Lewis acid sites useful in gas storage, gas separation, and catalysis.[127-129] However, introducing Bronsted acid sites into MOFs is quite difficult because most of the MOFs cannot survive under acidic conditions, not to mention coexisting with strong acidic groups such as sulfonic acid.[130] UiO-66-type MOFs may be exceptions because of their extra high chemical stability. Kitagawa and his co-workers reported the direct synthesis of UiO-66(Zr)-SO_3H and found that the framework collapsed upon activation possibly because of the pendent sulfonic groups that may attack and thus degrade the Zr SBUs.[131] Post-synthetic sulfonation is an alternative and effective option to prepare MOFs tethered with sulfonic acid groups (Fig. 7).[132] For example, Chen *et al.* used chlorosulfonic acid to prepare sulfonic acid-functionalized MOFs (MOF-SO_3H) and found that UiO-66-SO_3H could act as solid acids to catalyse fructose transformation to 5-hydroxymethylfurfural (HMF) with a high yield of 85% and a full fructose conversion at 120 °C for 60 min in DMSO.[101]

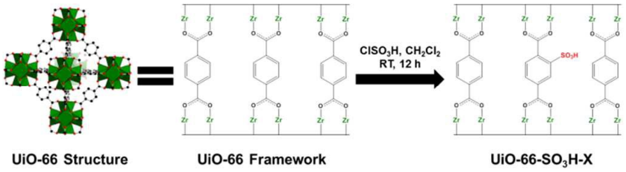

Fig. 7 Synthetic route of UiO-66-SO_3H-X.

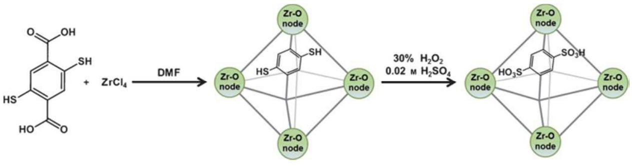

Fig. 8 Synthetic route of UiO-66-$(SO_3H)_2$.[103] Reprinted with permission from John Wiley and Sons Copyright 2015.

Likewise, bisulfonic acid attached UiO-66(Zr)-$(SO_3H)_2$ could not be directly synthesized but can also be obtained by post-synthetic method. Hong *et al.* successfully developed UiO-66(Zr)-$(SO_3H)_2$ through a two-step process (Fig. 8).[103] UiO-66(Zr)-$(SH)_2$ was initially prepared by solvothermal synthesis and then underwent a complete *in situ* thiol oxidation process to be converted into UiO-66(Zr)-$(SO_3H)_2$.[133] The high density of sulfonic acid groups gave this MOF an ultrahigh proton conductivity of 8.4×10^{-2} S cm^{-1}. However, its thermal stability and cycle performance still remain to be further optimized.

Based on the above discussion, post-synthetic sulfonation remains a dominant and effective way to tether Bronsted acid groups into UiO-66-type MOFs. Nevertheless, this method has several limitations and straightforward strategies are highly desired in the future to synthesize sulfonated MOFs for the applications such as catalysis or proton conductivity.

5.2 Functionalization with bioactive molecules

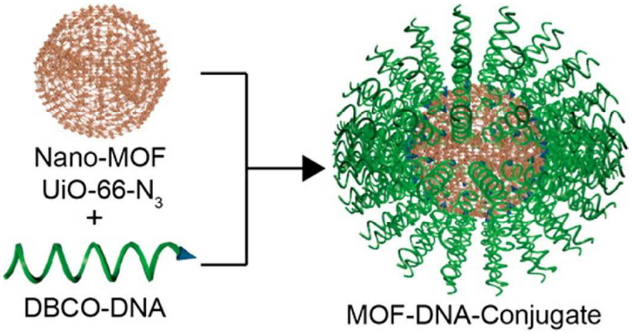

Fig. 9 Scheme for DNA functionalization of UiO-66(Zr)-N_3 nanoparticles.[134] Reprinted with permission from American Chemical Society Copyright 2014.

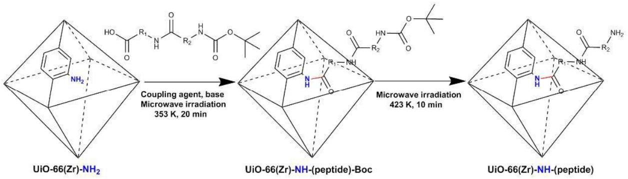

Fig. 10 Simplified scheme for two-step process of peptide grafting into UiO-66(Zr)-NH_2.

Tethering bioactive molecules on or into MOFs for highly value-added applications should be of potential interest because the tethered bioactive molecules can introduce new properties, such as confined microenvironment, bio-specific interactions, and localized heterogeneity.[135] However, handling bioactive molecules is not easy. Any processes containing thermal treatment, polarity change, or pH change may jeopardize or even completely destroy their bio-activities. In 2014, Mirkin and his co-workers reported the first example of MOF nanoparticle–nucleic acid (DNA strand) conjugates (Fig. 9).[134] They have successfully attached oligonucleotides onto the surface of UiO-66(Zr)-N_3 nanoparticles via click chemistry. They have also proven that the stability of MOF nanoparticles had been largely increased, which is highly promising for intracellular gene regulation applications. Canivet and his co-workers covalently anchored enantiopure peptides into UiO-66(Zr)-NH_2 cavities through microwave-assisted post-synthetic modification (Fig. 10).[136] Their results have provided a paradigm to design a library of peptide/MOF composites with confined and asymmetric active groups for possible bio-catalytic applications. However, for the modification of UiO-66-type MOFs with biomolecules, pore size can be an important limitation. It would be more feasible if other stable UiO-type MOFs with prolonged ligands and enlarged pore size (e.g. UiO-67, UiO-68) can be applied to broaden the applications in host-guest chemistry.

5.3 Surface coating

The surface properties of MOFs (e.g. hydrophobicity) may affect their performance in some applications such as post-combustion CO_2 capture, where a hydrophobic surface is preferred to minimize the effect of moisture.[137] Coating MOF particles with hydrophobic polymers may be a feasible way to adjust the surface properties of MOF particles. For example, Son *et al.* applied Sonogashira coupling between tetra (4-ethynylphenyl) methane with 1, 4-diiodobenzene or 4, 4'-diiodobiphenyl to form a hydrophobic microporous organic network (MON) coating outside of UiO-66(Zr)-NH_2 (Fig. 11).[138] They have shown that water contact angle (an indicator of the hydrophobicity of material surface) could be gradually tuned from 0° (highly hydrophilic, UiO-66(Zr)-NH_2) to as high as 145° (highly hydrophobic, MOF@MON-3) by a simple control of the thickness of MON layers. This work has proven that the external surface properties of MOFs can be chemically tuned. It also suggests a new way to design MOF/polymer core-shell composites as well as to prepare hollow microporous polymers if the MOF cores can be removed later on. Besides, a lot of research has been devoted to the surface functionalization of UiO-66,[139] UiO-66(Zr)-NH_2.[95, 140], UiO-66-NH-PNIPAM,[141] AS-UiO-66-Pd.[142]

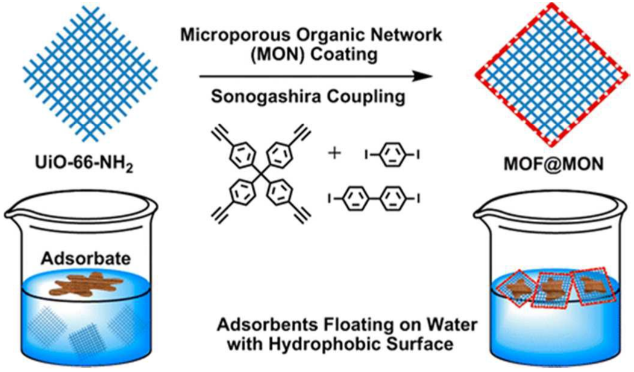

Fig. 11 Scheme for microporous organic network (MON) coating on UiO-66-NH_2.[138] Reprinted with permission from American Chemical Society Copyright 2014.

5.4 Nanoparticle embedment

One of the fundamental strategies to enhance the catalytic activity of metal-based catalysts is to decrease their particle size to nanometer range or even single atom form for the sake of exposing as many surface atoms as possible.[143] Embedding metal nanoparticles on porous supports is an important method in the design of new catalysts. Because of their small pore size (0.3-10 nm), MOFs are ideal platforms to confine metal particles into nanometer or nanocluster range and suppress their aggregation. For example, Somorjai *et al.* reported a growth of a series of nanocrystalline MOFs incorporating platinum metal nanocrystals (NCs).[144] They have proven that Pt⊂nMOF could act as a highly efficient and selective catalyst for methylcyclopentane (MCP) hydrogenative conversion. Meanwhile, it has also been demonstrated to be capable of lowering the temperature of C−C and C−H bond activation reactions by 100 °C. More recently, in order to tune the chemical microenvironment of the resultant catalysts, they systematically controlled the Pt nanoparticles embedment inside UiO-66(Zr)-type MOFs with functional acidic and/or basic groups (Fig. 12).[145] They have proven that a combination of more than one functional group was not just a simple superposition of the product but also demonstrated some synergistic effect. Their results provided an incisive and enlightening perspective for not only the design of MOF-supported metal nanoparticle catalysts but also the extension of MOFs as porous platforms for anchoring other kinds of nanoparticles. Besides, other kinds of functional moieties, such as drug,[146] metal oxides[147-150] or complex,[151-153] ionic liquid,[154] metal nanoparticles (e.g. Pt,[155-159] Au,[160-162] Ag,[163] Ru,[164] Ni and Mg[165]), acid or base tags,[166-168] etc. have also been reported to be tethered inside UiO-66-type MOFs for drug deliver or catalysis applications.

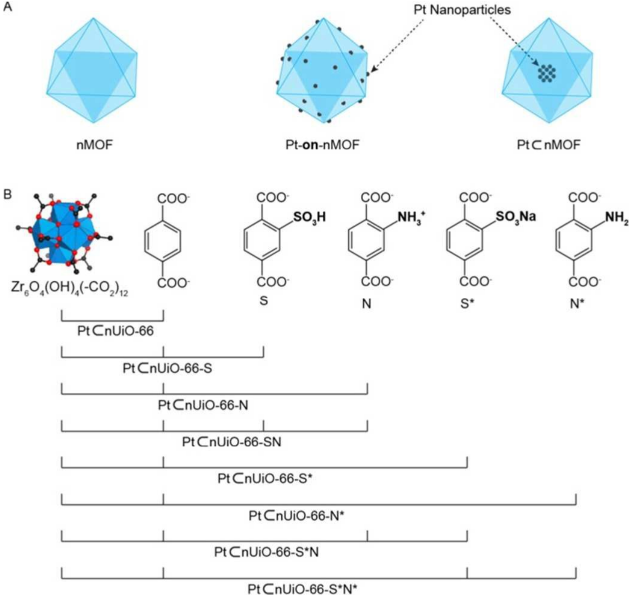

Fig. 12 Schematic representation for the preparation of nMOF and Pt-loaded nMOFs.[145] Reprinted with permission from American Chemical Society Copyright 2015.

5.5 Cation exchange

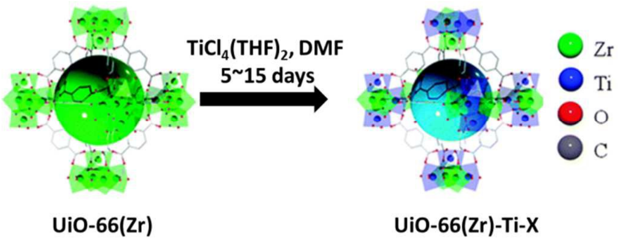

Fig. 13 Scheme for metal cation exchange of UiO-66(Zr) with Ti(IV) salts.[169, 170] Reprinted with permission from The Royal Society of Chemistry Copyright 2013.

Introducing extra metal cations into MOFs is an effective way to generate heterogeneity inside MOFs because different metals have different coordination modes and affinity toward guest molecules.[8] Metal cation exchange is such a way to endow MOFs with different metals. This approach has been applied to the synthesis of isostructural MOFs that cannot be directly synthesized, such as Cr^{3+}/Ti^{3+} substituted MOF-5,[171] Ti^{4+}/Hf^{4+}/Ce^{4+} substituted or functionalized UiO-66(Zr).[170, 172-174] In particular, it may be applied to Group IV elements such as Ti, Zr, and Hf for UiO-66-type MOFs. Both Zr[29] and Hf[47] can form UiO-66-type MOFs, while reacting BDC ligand with Ti metal sources can only afford MIL-125 which does not belong to the UiO-66 series.[49] Theoretically speaking, UiO-66 with Ti as the metal nodes should be of great interests because it can potentially exhibit both high stability and photoactive activity serving as an excellent photocatalyst.[49] Nevertheless, to the best of our knowledge, UiO-66(Ti) has not been reported yet. Recently, Hill *et al.* have used $TiCl_4(THF)_2$ DMF solution to conduct Ti metal cation exchange with UiO-66(Zr) and successfully obtained Ti-substituted UiO-66(Zr) with the substitution percent as high as 56% (Fig. 13).[169] They have also demonstrated that Ti-substituted UiO-66 has smaller pores with increased gravimetric CO_2 uptake capacity partially due to the reduced crystal density as Ti is lighter than Zr. This study suggests a promising future of UiO-66(Ti) with wide applications in gas separation and catalysis.

5.6 Ligand exchange

Unlike cation exchange, post-synthetic ligand exchange (PSLE) refers to ligand substitution instead. Cohen and his co-workers have carried out comprehensive studies of the mechanism, operation, and applications of this approach.[4, 5, 7, 11, 175-178] Herein, we will focus on the discussion of PSLE in UiO-66(Zr). The first example of PSLE study in UiO-66(Zr) originally regarded as “inert” was reported in 2012.[170, 179] A series of BDC-type functional ligands were exchanged with the BDC inside UiO-66(Zr) affording new bi or tri-functional UiO-66(Zr)-type MOFs (Fig. 14). Recently, UiO-66(Zr)-type MOFs containing metal binding groups such as hydroxyl[180, 181] (for Fe^{3+}, Cr^{3+}) and thiol[182] (for Pd^{2+}) groups were also synthesized using PSLE approach. When bound with metals, these MOFs could act as highly efficient catalysts for oxidation and selective C−H functionalization reactions. In a short summary, PSLE has been proven to be a facile and mild approach to endow UiO-66-type MOFs with various functional groups to broaden their applications in gas sorption, heterogeneous catalysis, etc.

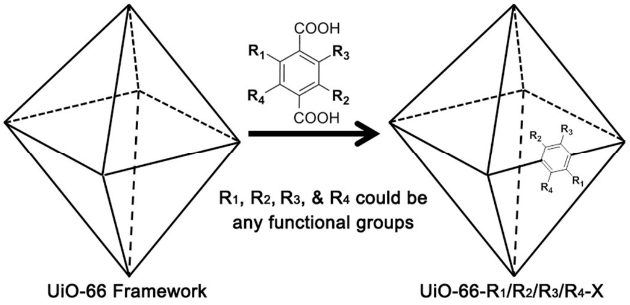

Fig. 14 Scheme for post-synthetic ligand exchange of UiO-66-type MOFs.[170, 179, 181, 183]

5.7 Crosslinking

In polymer chemistry, crosslinking refers to the formation of bonds (covalent or ionic) that link one polymer chain to another.[184] Given the rich functional groups within MOFs that can be cross-linked, such as carboxylic, amine, and hydroxyl groups, crosslinking may be another approach to tune the porosity and functionality of the frameworks. For example, Clet *et al.* used a simple thermal heating method to crosslink UiO-66(Zr)-$(COOH)_X$ (x = 1 or 2) via the formation of anhydride bonds (Fig. 15).[185] They have demonstrated that water molecules could be easily and reversibly stored and released within the cross-linked MOF, which may find applications in water storage, electric dehumidifiers, and thermal batteries.[30] Admittedly, the crosslinking chemistry of MOFs remains rarely explored and challenging. This is probably because the introduction of external stimuli such as heat, vacuum, and chemicals may undermine the stability of MOFs.[20] However, this approach has the potential to be further developed for the fabrication of smart device.[186]

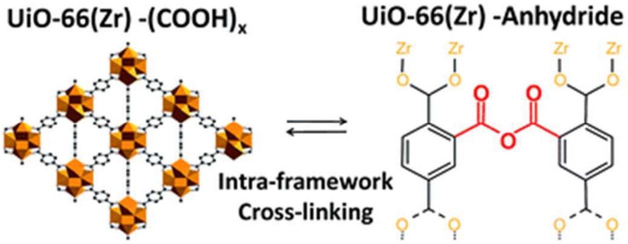

Fig. 15 Acid-functionalized UiO-66(Zr) MOFs and their evolution after intra-framework cross-linking.[185] Reprinted with permission from The Royal Society of Chemistry Copyright 2015.

5.8 Ionization/Metalation

Introducing free metal cations into MOFs, a process called ionization or metalation, may change the polarity of MOFs to endow them with new features. This operation can be easily achieved by a simple acid-based reaction between metal hydroxide solutions and MOFs with dangling acid groups (e.g. sulfuric acid, carboxylic acid). In our previous research, we have adopted this strategy to functionalize UiO-66(Zr)-SO_3H[91] and UiO-66(Zr)-$(COOH)_2$[105] with different alkaline metal cations, such as Li^+, Na^+, K^+, and Rb^+ (Fig. 16). The prepared MOFs have been demonstrated to have largely improved gas separation performance possibly due to stronger gas-MOFs interactions. Although relying on the development of MOFs with dangling acidic groups and fine control of the acid-base neutralization reactions, the simple operation and effectiveness make this approach an important one for the post-synthetic modification of UiO-66-type MOFs.

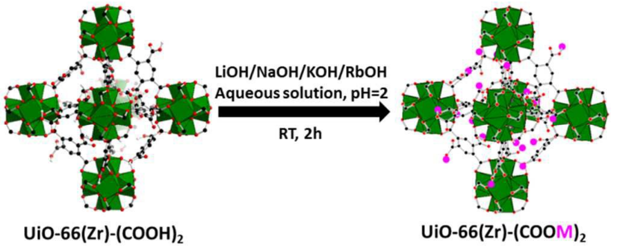

Fig. 16 Scheme for direct ionization or metalation of functional UiO-66(Zr)-$(COOH)_2$ to produce ionized MOFs.[105]

5.9 Mixed ligand strategy

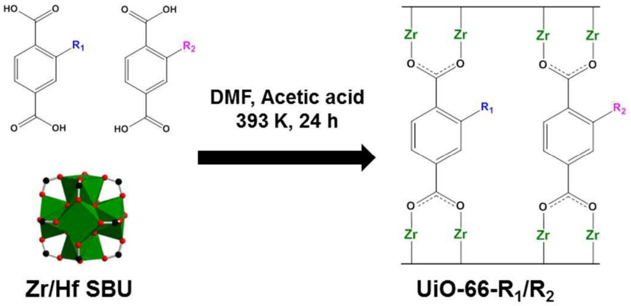

Fig. 17 Scheme of mixed ligand approach for the synthesis of multi-functional UiO-66-type MOFs.[187, 188]

Employing two or more ligands with different functional groups to conduct isostructural MOF synthesis could potentially introduce asymmetry, heterogeneity, and possible synergistic effects into the resultant MOFs.[187, 189-193] Mixed ligand strategy has thus been applied to endow UiO-66-type MOFs with dual functionalities (Fig. 17). The first study on using mixed ligands in UiO-66(Zr) was conducted by Cohen and his co-workers, where a mixture of BDC-NH_2 and BDC-Br was used to form UiO-66-Br-NH_2.[122] They have found that mixed ligand-based MOF was more thermally stable than pristine UiO-66-NH_2. Recently, Bordiga *et al.* also applied this strategy to prepare a series of UiO-66-type MOFs with different ratios of BDC over BDC-NH_2.[187] They have also demonstrated that the chemical stability of the resultant MOFs could be increased. Moreover, the porosity could be tuned by varying the feed ratio between BDC-NH_2 and BDC. Based on the above results, mixed ligand strategy can not only tune the porosity, but also enhance both thermal and chemical stability of the resultant MOFs. Given a rich library of BDC-type ligands shown in Fig. 1e, a large combination of ligands can be visualized and readily available for the design of dual/multi-functional UiO-66-type MOF hybrid materials.

5.10 Two/multi-step PSMs

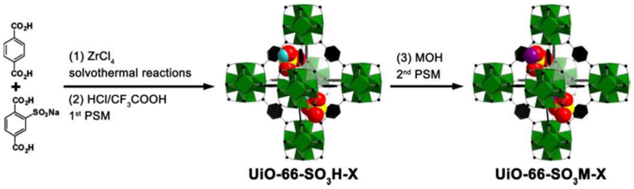

Fig. 18 Synthesis of UiO-66-SO_3M-X involving mixed ligand and post-synthetic metalation.[91] Reprinted with permission from John Wiley and Sons Copyright 2014.

The combination of any two or more strategies mentioned above, also called two/multi-step PSMs, may be promising for the design of multifunctional MOF hybrid materials. For example, in our previous study, we have adopted a combination of mixed ligand strategy and metalation (Fig. 18) to prepare a series of UiO-66-SO_3M-X (M=Li, Na, K, Rb).[91] The resultant MOFs showed largely enhanced CO_2 uptake, CO_2/N_2 and CO_2/CH_4 selectivity. Recently, Cohen and his co-workers adopted continuous two-step PSM (ligand exchange followed by metalation) to synthesize a series of transition metal based UiO-66-type MOFs (Fig. 19).[180, 182] They have demonstrated that this two-step PSM could be a great add-up to single-step PSM, and can facilely incorporate active metal sites inside MOFs which are originally without binding sites. The resultant materials are highly promising for gas separation and catalysis applications.

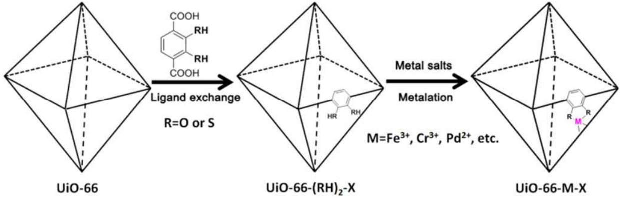

Fig. 19 Synthesis of functional UiO-66-type MOFs involving post-synthetic ligand exchange and metalation.[180, 182]

6. UiO-66-type MOF membranes

Because of the features such as continuous operation, high efficiency, and relatively low cost, membrane technology has been widely used in industry for gas and liquid separation processes, such as steaming gas reforming, natural gas upgrading, etc.[194-197] In this section, we will introduce some significant advances in UiO-66-type MOF membranes and composite membranes that can complement pure MOFs for separation applications.

6.1 Pure UiO-66 membranes

The concept of pure MOF membranes is appealing as their structural features such as uniform yet tunable pore size and pore functionalities may endow the resultant membranes with large throughput and excellent selectivity.[198] Since 2005, a lot of pure MOF membranes, such MOF-5,[199] HKUST-1,[200] MIL-53,[201] ZIF-8,[202] etc. have been synthesized and tested for gas separation. However, it is still quite challenging to prepare continuous MOF membranes on porous supports without defects by direct solvothermal synthesis. This is because of the heterogeneous nucleation of MOF crystals on the surface of support that may not be sufficient to evenly cover the whole surface.[198] This issue is more challenging for UiO-66-type MOF membranes because of the slow growth kinetics of these MOFs.[203] Initially, researchers are trying to grow UiO-66-type MOF thin films on flat silicon substrates by solvothermal approach[204] and on electrodes through electrodeposition.[205, 206] However, the procedures are complex and potential applications remain to be explored thoroughly. Recently, a major breakthrough has been made by Li and his co-workers.[203] In this work, continuous UiO-66(Zr) polycrystalline membranes were fabricated on alumina hollow fiber supports by in situ solvothermal synthesis (Fig. 20). The obtained MOF membrane exhibited excellent multivalent ion rejection separation performance (e.g., 86.3% for Ca^{2+}, 98.0% for Mg^{2+}, and 99.3% for Al^{3+}), moderate permeance (0.14 L m^{-2} h^{-1} bar^{-1}), good permeability (0.28 L m^{-2} h^{-1} bar^{-1} μm), and excellent recyclability, which can be quite promising for sea water desalination. Considering the wide choice of ligand used in UiO-66-type MOFs, we can expect more pure UiO-66 membranes to be reported in the near future.

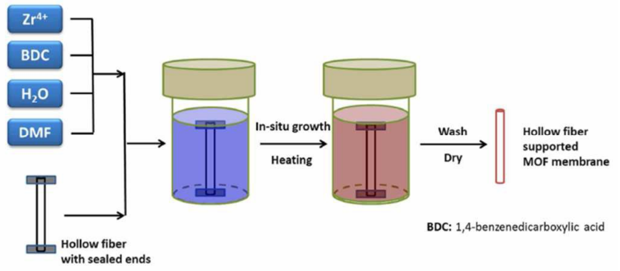

Fig. 20 Scheme for direct preparation of pure UiO-66(Zr) membranes supported on porous ceramic hollow fibers.[203] Reprinted with permission from American Chemical Society Copyright 2015.

6.2 Mixed matrix membranes

Mixed matrix membranes (MMMs), comprising inorganic functional fillers and continuous polymer matrices, have emerged as a promising technology combining both the easy processability of polymers and high separation performance of inorganic fillers, and are highly beneficial to overcome the trade-off between permeability (throughput) and selectivity (efficiency) of pure polymeric membranes.[197] By nature, MOFs can act as ideal inorganic fillers to be embedded into polymer matrices because the pore size, shape, and functionality of MOFs can be tuned over a large range in order to meet different separation requirements. For this application, UiO-66-type MOFs have at least three advantages: (1) inherently suitable MOF particle size within 100 nm to 500 nm that makes it easy to be mixed with polymers; (2) wide tunability of the pore size and functionality, which can be readily realized by ligand selection and PSMs; (3) excellent mechanic and chemical stability that allow the MOFs to survive during membrane preparation and in harsh working conditions. The first example of UiO-66-containing MMMs was reported by Kaliaguine in 2012.[207] They used synthetic polyimide [4,4'-(hexafluoroisopropylidene)diphthalic anhydride(6FDA)-4,4'-oxydianiline(ODA)] as the continuous polymeric matrices and found that by incorporating both UiO-66(Zr) and UiO-66(Zr)-NH_2, the CO_2/CH_4 perm-selectivity of the membranes could be largely enhanced compared to the neat polyimide (6FDA-ODA) membranes. However, the separation performance is not satisfied because the as-prepared membranes cannot surpass the 2008 Robinson upper bound which represents state-of-the-art performance of pure polymeric membranes.[208, 209] Later on, several other MMMs containing UiO-66-tye MOFs were reported to have high gas separation performance.[210, 211] Recently, Hill and his co-workers have prepared pristine and Ti-exchanged UiO-66(Zr)@PIM-1 (PIM stands for polymers of intrinsic microporosity) MMMs. They have found that Ti incorporation helped to increase the gas permeability more than doubled without a loss in selectivity (Fig. 21).[212] This could be possibly attributed to an increased affinity of CO_2 and stronger interactions between polymer matrices and Ti-MOFs. As a result, a slight loading (5 wt%) of MOFs could improve the membrane performance dramatically to surpass the 2008 CO_2/N_2 Robeson upper bound.

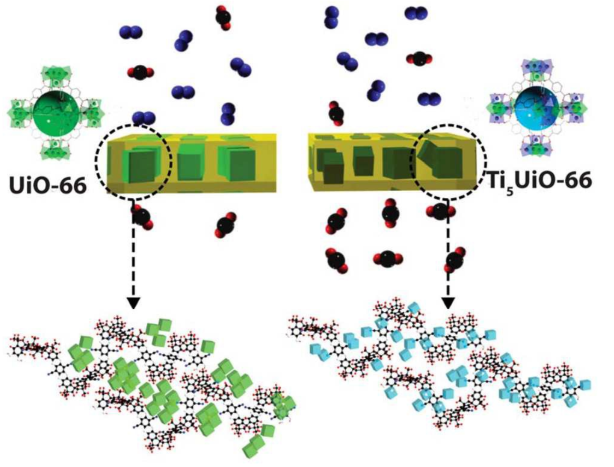

Fig. 21 Scheme for Ti-loaded UiO-66@PIM-1 MMMs.[212] Reprinted with permission from Nature Publishing Group Copyright 2015.

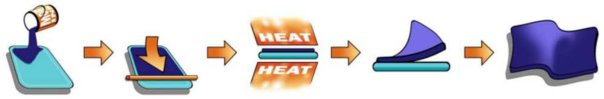

Fig. 22 Scheme for drawdown coating process for the fabrication of freestanding UiO-66@PVDF MMMs.[213] Reprinted with permission from John Wiley and Sons Copyright 2015.

Cohen group has prepared a series of MMMs containing high loading amounts of various MOFs including UiO-66 (Fig. 22).[213] They have proved that the surface area of incorporated MOFs within MMMs remained unaffected. In addition, post-synthetic modification and post-synthetic exchange processes can be readily applied to the MOFs within MMMs, opening up new directions toward the functionalization of MOF-containing MMMs.

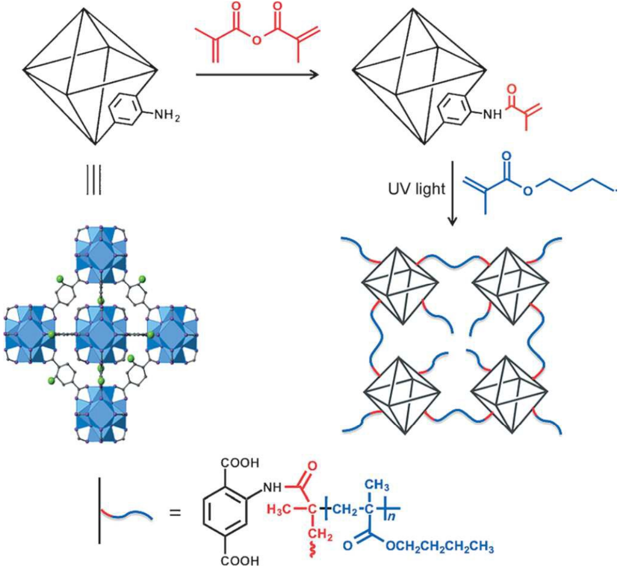

Fig. 23 Scheme for the preparation of flexible stand-alone membranes by copolymerization of methacrylic anhydride functionalized UiO-66(Zr)-NH$_2$ nanocrystals with butyl methacrylate (BMA) under UV light irradiation.[214] Reprinted with permission from John Wiley and Sons Copyright 2015.

Wang and his co-workers adopted a photo-induced postsynthetic polymerization (PSP) strategy to covalently link methacrylic anhydride functionalized UiO-66(Zr)-NH$_2$ nanocrystals with butyl methacrylate (BMA) through polymerization (Fig. 23).[214] After a delamination from Teflon mould, an elastic and standalone membrane could be obtained, which had been proven to be capable of removing heavy metal contaminants such as Cr^{VI} ions from water. One advantage of this method that differentiates it from other MMM fabrication processes is that it could endow embedded MOF powders with certain elasticity, processability, and flexibility.

One of the major remaining issues for MMM study is the compatibility between MOF fillers and polymeric matrices. In addition, the effect of MOF morphology on the performance of membrane is an interesting topic to be studied. Last but not least, a further development of novel UiO-66-type MOFs with high stability and required functionality is another direction to pursuit.

7. Defects of UiO-66-type MOFs

Defects in MOFs have received a lot of attention recently because these defects may weaken the stability of MOFs but on the other hand could possibly bring some advantages such as extra porosity and Lewis acid sites that are useful in various applications.[215-217] In principle, a perfect UiO-66 crystal should have a 12-connected framework structure. However, it may not always be the case in reality. Lamberti *et al.* firstly addressed the presence of defects in UiO-66 by using thermogravimetric analysis (TGA).[64] They have found that around 1/12 missing BDC ligands occurred randomly in the framework. Nevertheless, it is still a rough estimation of the defect concentration inside UiO-66 frameworks. Directly visualization of defects through crystallographic methods is thus highly desired but more challenging due to the random distribution of defects as well as the small crystal size of UiO-66-type MOFs. In 2013, Zhou and his co-workers firstly confirmed the structural evidence of defects inside UiO-66(Zr) using neutron diffraction technique.[218] According to their refined linker occupancies, an average of 1/12 BDC ligands were found missing, which is in excellent agreement with Lamberti's results. The presence of defects effectively reduced the network connection from 12 to 11, possibly accounting for compromised framework stability. Moreover, they have demonstrated that these defects could increase the porosity of MOFs from 0.426 to 0.502 cm^3 g^{-1} and surface area from 954 to 1433 m^2 g^{-1}. Besides, they were able to tune the defect concentration by varying the ratio of modulators thus to adjust the porosity from 0.44 to 1.0 cm^3 g^{-1} and BET surface area from 1090 to 1617 m^2 g^{-1}. Enlightened by these pioneering studies, many research efforts have been devoted recently to the characterization and control of defects as well as the applications of defect-present UiO-66-type MOFs. Lillerud *et al.* utilized synchrotron single-crystal X-ray diffraction to disclose the structure of both UiO-66(Zr) and UiO-67(Zr).[219] They have disentangled the μ_3-O position of the prismatic faces of the Zr$_6$ octahedron into two distinct μ_3-O and μ_3-OH, with occupancy of 0.5 each. Snurr *et al.* studied the effect of location of defects on water sorption in UiO-66(Zr) and found that the missing linkers could make UiO-66(Zr) more hydrophilic.[220]

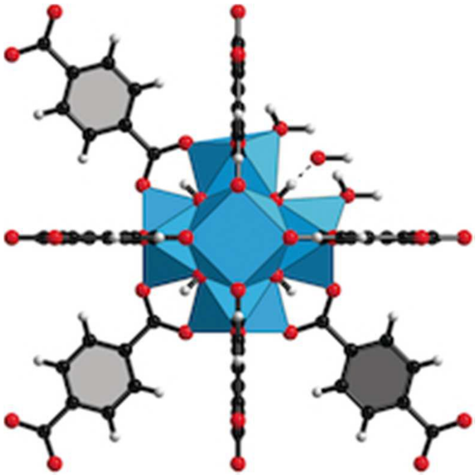

Fig. 24 Schematic illustration of defect sites in UiO-66 single crystals. The missing BDC ligand is replaced by water molecule and overall charges are counterbalanced by hydroxide anions hydrogen bonded within the pores of the framework. Reprinted with permission from John Wiley and Sons Copyright 2015.[80]

More recently, Yaghi and his co-workers conducted a single-crystal X-ray diffraction study of the defects in UiO-66 single crystals with a size of ~300 μm.[80] They have proven that the water molecules primitively coordinated to the zirconium centers were responsible for the missing linker defects and replaced the BDC linkers, whereas overall charges were counterbalanced by hydroxide anions hydrogen bonded within the pores of the framework (Fig. 24). This is a pioneering characterization of defects in UiO-66-type MOFs with molecular level precision, and has opened up a new realm of studying point defects in similar MOFs of microcrystalline nature.

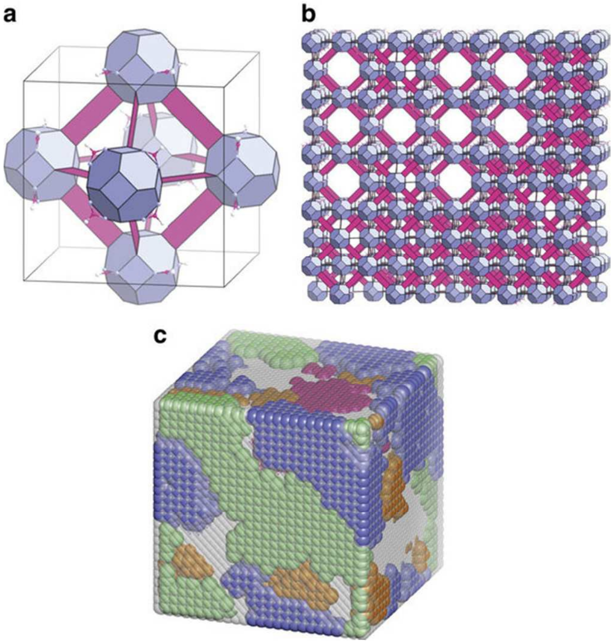

Fig. 25 Structural description of defect nano-regions in UiO-66(Hf). (a) Polyhedral representation of a single-unit cell of the ordered *reo* defect structure; (b) atomistic model representative section; (c) atomistic representations of defect nano-regions in UiO-66(Hf). Nano-domains corresponding to each of these four orientations are represented by blue, green, orange and magenta regions. Grey-colored regions correspond to defect-free fcu framework.[67] Reprinted with permission from Nature Publishing Group Copyright 2014.

The control of ordered defects in UiO-66-type MOFs should be helpful to understand their structural imperfection and potential applications. The starting point of controlled imperfection is to see if the defects can be completely eliminated to get perfect UiO-66 crystals. Lillerud and his co-workers have carried out such a study and successfully “ironed out” all the defects by increasing the synthetic temperature from 120 to 220 °C and adjusting BDC to Zr molar ratio from 1 to 2.[221] The resultant ideal UiO-66(Zr) was found to be of unsurpassed thermal stability. Secondly, the establishment of a correlation between defects is of great significance. In 2014, Goodwin and his co-workers have demonstrated that correlations between defects can be introduced and further controlled within UiO-66(Hf), which was co-evidenced by a combination of diffuse scattering, electron microscopy, anomalous X-ray scattering, and pair distribution function (Fig. 25).[67, 222] In specific, the nano-region was dominated by eight connecting clusters to form a short-range-ordered defects leading to a *reo* topology.[223] Afterwards, Speybroeck *et al.* used both experimental and theoretical techniques to intentionally generate defects (active sites) inside UiO-66(Zr) by adding strong modulators such as HCl and TFA.[224] They have found that well-tuned UiO-66(Zr) could largely enhance catalytic citronellal cyclization toward isopulegol.

More recently, Kitagawa and his coworkers exquisitely tuned the defects in UiO-66(Zr) with a range of defect concentration in order to create Lewis acidic sites.[225] It is proposed that the exposed Lewis sites, when attached by water (pKa ≤ 0.3), could act as a highly acidic proton source. They have demonstrated that by controlled generation of defects, the proton conductivity can be exponentially increased by nearly 3 orders of magnitude from 1.30×10^{-5} S cm^{-1} to 6.93×10^{-3} S cm^{-1} at 65 °C and 95% relative humidity. In contrast, they systematically studied the role of 3D ordered defects on the physical properties of UiO-66-SO_3H.[226] In detail, by tuning the defect concentration, they achieved a much higher proton conductivity of 5.62×10^{-3} S cm^{-1} at the same testing conditions. Their results are not only important for exploring MOFs for proton conduction applications but also insightful in unveiling the stability and limitations of MOFs with ordered defects.

8. Summary and outlook

In this perspective, we have reviewed the *de facto* methodologies toward the synthesis and scale-up production of UiO-66-type MOFs and membrane materials. Compared to the synthesis of other MOFs, the synthesis of UiO-66-type MOFs is more empirical, complicated, and unpredictable. Although the current modulator-based (both solvothermal and hydrothermal) approach has been proven to be helpful, the repeatable and scale-up synthesis of UiO-66-type MOFs with excellent crystallinity and surface area still remains as a challenge. Therefore, novel synthetic approaches toward the repeatable, scalable, and green production of UiO-66-type MOFs, especially those containing Ti and Hf, are highly desired and worth of further study. Besides, multivariate (MTV)[189] UiO-66-type MOFs with different metals or ligands are of great interest because they may exhibit synergistic effects useful in separation and catalysis applications. Further study in this direction needs to be developed as well.

Apart from synthesis, the microstructure-property relationship is also worth of comprehensive studies for UiO-66-type MOFs. The importance of growing large single crystals suitable for X-ray diffraction studies has been demonstrated in Yaghi's work.[80] With the single crystal X-ray diffraction data, the details of precise atom positions, bond twisting angles, and coordination numbers could be facilely disentangled and soundly set. Normally, defects are unwelcome in typical material research as they may undermine the macroscopic properties of materials such as stability and mechanical properties. Admittedly, defects may also compromise the thermal or chemical stability of UiO-66-type MOFs to a certain degree, but they would also generate porosity and introduce extra Lewis acid sites which are highly beneficial for gas sorption and heterogeneous catalysis applications. Although in its infant stage, studies regarding the manipulation or even precise control of defects within MOFs especially UiO-66-type MOFs will continue and prosper in the near future.

Although not being covered in this perspective, the study of macroscopic properties of UiO-66-type MOFs such as electric, optical, and mechanical behaviour is at least an equally important research direction because further study of UiO-66-type MOFs will finally lead to their commercialization and large-scale applications. In that case the macroscopic properties of materials will start to dominate their final applications. Considering their high stability, versatile functionality, and relatively mild synthetic conditions, we believe UiO-66-type MOFs are among those MOFs that are most promising to be commercialized for large-scale applications.

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Abbreviations

MOFs	metal-organic frameworks
UiO	university of Oslo
MIL	Matérial Institut Lavoisier
Ti	Titanium
Zr	zirconium
Hf	hafnium
CUSs	coordinative unsaturated sites
UMCs	unsaturated metal centers
DMF	N, N'-dimethylformamide
DEF	N, N'-diethylformamide
DMA	N, N-dimethylacetamide
AA	acetic acid
FA	formic acid
HCl	hydrochloride acid
TFA	trifluoroacetic acid
FMA	fumaric acid
SA	squaric acid
BDC	1, 4-benzenedicarboxylic acid
BPDC	4, 4'-biphenyl-dicarboxylate
TPDC	terphenyl dicarboxylate
BDC-F	2-fluoroterephthalic acid
BDC-Cl	2-chloroterephthalic acid
BDC-Br	2-bromoterephthalic acid
BDC-I	2-iodoterephthalic acid
BDC-OH	2-hydroxyterephthalic acid
BDC-SH	2-mercaptoterephthalic acid
BDC-CH_3	2-methylterephthalic acid
BDC-NO_2	2-nitroterephthalic acid
BDC-NH_2	2-aminoterephthalic acid
BDC-Naphthyl	naphthalene-1, 4-dicarboxylic acid
BDC-SO_3H	2-sulfoterephthalic acid
BDC-CF_3	2-(trifluoromethyl) terephthalic acid
BDC-COOH	benzene-1, 2, 4-tricarboxylic acid
BDC-2, 3-$(OH)_2$	2, 3-dihydroxyterephthalic acid
BDC-2, 3-$(SH)_2$	2, 3-dimercaptoterephthalic acid
BDC-$(F)_2$	2, 5-difluoroterephthalic acid
BDC-$(Cl)_2$	2, 5-dichloroterephthalic acid
BDC-$(Br)_2$	2, 5-dibromoterephthalic acid
BDC-$(I)_2$	2, 5-diiodoterephthalic acid
BDC-$(OH)_2$	2, 5-dihydroxyterephthalic acid
BDC-$(SH)_2$	2, 5-dimercaptoterephthalic acid
BDC-$(CH_3)_2$	2, 5-dimethylterephthalic acid
BDC-$(NH_2)_2$	2, 5-diaminoterephthalic acid
BDC-$(CF_3)_2$	2, 5-bis (trifluoromethyl) terephthalic acid
BDC-$(OCH_3)_2$	2, 5-dimethoxyterephthalic acid
BDC-$(COOH)_2$	benzene-1, 2, 4, 5-tetracarboxylic acid
BDC-$(SO_3H)_2$	2, 5-disulfoterephthalic acid
BDC-$(OCH_2CH_3)_2$	2, 5-diethoxyterephthalic acid
BDC-$(CH(CH_3)_2)_2$	2, 5-diisopropylterephthalic acid
BDC-$(F)_4$	2, 3, 5, 6-tetrafluoroterephthalic acid
BDC-$(OH)_4$	2, 3, 5, 6-tetrahydroxyterephthalic acid
BDC-$(CH_3)_4$	2, 3, 5, 6-tetramethylterephthalic acid
BDC-$(CF_3)_4$	2, 3, 5, 6-tetrakis (trifluoromethyl) terephthalic acid
BDC-$(COOH)_4$	benzene-1, 2, 3, 4, 5, 6-hexacarboxylic acid
MHT	modulated hydrothermal
HKUST	Hong Kong University of Science and Technology
PDMS	polydimethylsiloxane
PFA	perfluoroalkoxyalkane
SBUs	secondary building units
HMF	5-hydroxymethylfurfural
MON	microporous organic network
nMOFs	nanocrystalline metal−organic frameworks
NCs	nanocrystals
MCP	methylcyclopentane
THF	Tetrahydrofuran

MMMsMixed matrix membranes
6FDA4, 4’-(hexafluoroisopropylidene) diphthalic anhydride
ODA4, 4’-Oxydianiline
PIMpolymers of intrinsic microporosity
PVDFpolyvinylidene fluoride
BMAbutyl methacrylate
SXRDsingle-crystal X-ray diffraction
MTVmultivariate

References

1 B. F. Hoskins and R. Robson, Infinite polymeric frameworks consisting of three dimensionally linked rod-like segments, *J. Am. Chem. Soc.* **1989**, *111*, 5962-5964.

2 B. F. Hoskins and R. Robson, Design and construction of a new class of scaffolding-like materials comprising infinite polymeric frameworks of 3D-linked molecular rods. A reappraisal of the zinc cyanide and cadmium cyanide structures and the synthesis and structure of the diamond-related frameworks [N(CH3)4][CuIZnII(CN)4] and CuI[4,4',4'',4'''-tetracyanotetraphenylmethane]BF4.xC6H5NO2, *J. Am. Chem. Soc.* **1990**, *112*, 1546-1554.

3 H. Furukawa, K. E. Cordova, M. O'Keeffe and O. M. Yaghi, The chemistry and applications of metal-organic frameworks, *Science* **2013**, *341*, 1230444.

4 Z. Q. Wang and S. M. Cohen, Postsynthetic modification of metal-organic frameworks, *Chem. Soc. Rev.* **2009**, *38*, 1315-1329.

5 K. K. Tanabe and S. M. Cohen, Postsynthetic modification of metal-organic frameworks-a progress report, *Chem. Soc. Rev.* **2011**, *40*, 498-519.

6 N. Stock and S. Biswas, Synthesis of metal-organic frameworks (MOFs): routes to various MOF topologies, morphologies, and composites, *Chem. Rev.* **2012**, *112*, 933-969.

7 S. M. Cohen, Postsynthetic methods for the functionalization of metal-organic frameworks, *Chem. Rev.* **2012**, *112*, 970-1000.

8 C. K. Brozek and M. Dinca, Cation exchange at the secondary building units of metal-organic frameworks, *Chem. Soc. Rev.* **2014**, *43*, 5456-5467.

9 J. D. Evans, C. J. Sumby and C. J. Doonan, Post-synthetic metalation of metal-organic frameworks, *Chem. Soc. Rev.* **2014**, *43*, 5933-5951.

10 Z. Zhang and M. J. Zaworotko, Template-directed synthesis of metal-organic materials, *Chem. Soc. Rev.* **2014**, *43*, 5444-5455.

11 P. Deria, J. E. Mondloch, O. Karagiaridi, W. Bury, J. T. Hupp and O. K. Farha, Beyond post-synthesis modification: evolution of metal–organic frameworks via building block replacement, *Chem. Soc. Rev.* **2014**, *43*, 5896-5912.

12 O. M. Yaghi, M. O'Keeffe, N. W. Ockwig, H. K. Chae, M. Eddaoudi and J. Kim, Reticular synthesis and the design of new materials, *Nature* **2003**, *423*, 705-714.

13 N. W. Ockwig, O. Delgado-Friedrichs, M. O'Keeffe and O. M. Yaghi, Reticular chemistry: Occurrence and taxonomy of nets and grammar for the design of frameworks, *Acc. Chem. Res.* **2005**, *38*, 176-182.

14 M. O'Keeffe, Design of MOFs and intellectual content in reticular chemistry: a personal view, *Chem. Soc. Rev.* **2009**, *38*, 1215-1217.

15 D. Zhao, D. J. Timmons, D. Q. Yuan and H. C. Zhou, Tuning the Topology and Functionality of Metal-Organic Frameworks by Ligand Design, *Acc. Chem. Res.* **2011**, *44*, 123-133.

16 M. O’Keeffe and O. M. Yaghi, Deconstructing the Crystal Structures of Metal–Organic Frameworks and Related Materials into Their Underlying Nets, *Chem. Rev.* **2012**, *112*, 675-702.

17 W. Lu, Z. Wei, Z.-Y. Gu, T.-F. Liu, J. Park, J. Park, J. Tian, M. Zhang, Q. Zhang, T. Gentle Iii, M. Bosch and H.-C. Zhou, Tuning the structure and function of metal-organic frameworks via linker design, *Chem. Soc. Rev.* **2014**, *43*, 5561-5593.

18 V. Guillerm, D. Kim, J. F. Eubank, R. Luebke, X. Liu, K. Adil, M. S. Lah and M. Eddaoudi, A supermolecular building approach for the design and construction of metal-organic frameworks, *Chem. Soc. Rev.* **2014**, *43*, 6141-6172.

19 S. Furukawa, J. Reboul, S. Diring, K. Sumida and S. Kitagawa, Structuring of metal-organic frameworks at the mesoscopic/macroscopic scale, *Chem. Soc. Rev.* **2014**, *43*, 5700-5734.

20 T. R. Cook, Y.-R. Zheng and P. J. Stang, Metal–organic frameworks and self-assembled supramolecular coordination complexes: comparing and contrasting the design, synthesis, and functionality of metal–organic materials, *Chem. Rev.* **2013**, *113*, 734-777.

21 J. R. Long and O. M. Yaghi, The pervasive chemistry of metal-organic frameworks, *Chem. Soc. Rev.* **2009**, *38*, 1213-1214.

22 H. C. Zhou, J. R. Long and O. M. Yaghi, Introduction to metal-organic frameworks, *Chem. Rev.* **2012**, *112*, 673-674.

23 H.-C. Zhou and S. Kitagawa, Metal–Organic Frameworks (MOFs), *Chem. Soc. Rev.* **2014**, *43*, 5415-5418.

24 J. Canivet, A. Fateeva, Y. Guo, B. Coasne and D. Farrusseng, Water adsorption in MOFs: fundamentals and applications, *Chem. Soc. Rev.* **2014**, *43*, 5594-5617.

25 N. C. Burtch, H. Jasuja and K. S. Walton, Water Stability and Adsorption in Metal–Organic Frameworks, *Chem. Rev.* **2014**, *114*, 10575-10612.

26 G. Férey, C. Mellot-Draznieks, C. Serre, F. Millange, J. Dutour, S. Surblé and I. Margiolaki, A chromium terephthalate-based solid with unusually large pore volumes and surface area, *Science* **2005**, *309*, 2040-2042.

27 L. Bromberg, Y. Diao, H. M. Wu, S. A. Speakman and T. A. Hatton, Chromium(III) Terephthalate Metal Organic Framework (MIL-101): HF-Free Synthesis, Structure, Polyoxometalate Composites, and Catalytic Properties, *Chem. Mater.* **2012**, *24*, 1664-1675.

28 L. Alaerts, C. E. A. Kirschhock, M. Maes, M. A. van der Veen, V. Finsy, A. Depla, J. A. Martens, G. V. Baron, P. A. Jacobs, J. F. M. Denayer and D. E. De Vos, Selective adsorption and separation of xylene isomers and ethylbenzene with the microporous vanadium(IV) terephthalate MIL-47, *Angew. Chem., Int. Ed.* **2007**, *46*, 4293-4297.

29 J. H. Cavka, S. Jakobsen, U. Olsbye, N. Guillou, C. Lamberti, S. Bordiga and K. P. Lillerud, A new zirconium inorganic building brick forming metal organic frameworks with exceptional stability, *J. Am. Chem. Soc.* **2008**, *130*, 13850-13851.

30 H. Furukawa, F. Gándara, Y.-B. Zhang, J. Jiang, W. L. Queen, M. R. Hudson and O. M. Yaghi, Water Adsorption in Porous Metal–Organic Frameworks and Related Materials, *J. Am. Chem. Soc.* **2014**, *136*, 4369-4381.

31 B. Bueken, H. Reinsch, N. Reimer, I. Stassen, F. Vermoortele, R. Ameloot, N. Stock, C. E. A. Kirschhock and D. De Vos, A zirconium squarate metal-organic framework with modulator-dependent molecular sieving properties, *Chem. Commun.* **2014**, *50*, 10055-10058.

32 T.-F. Liu, D. Feng, Y.-P. Chen, L. Zou, M. Bosch, S. Yuan, Z. Wei, S. Fordham, K. Wang and H.-C. Zhou, Topology-Guided Design and

Syntheses of Highly Stable Mesoporous Porphyrinic Zirconium Metal–Organic Frameworks with High Surface Area, *J. Am. Chem. Soc.* **2015**, *137*, 413-419.

33 D. Feng, K. Wang, J. Su, T.-F. Liu, J. Park, Z. Wei, M. Bosch, A. Yakovenko, X. Zou and H.-C. Zhou, A Highly Stable Zeotype Mesoporous Zirconium Metal–Organic Framework with Ultralarge Pores, *Angew. Chem., Int. Ed.* **2015**, *54*, 149-154.

34 S. B. Kalidindi, S. Nayak, M. E. Briggs, S. Jansat, A. P. Katsoulidis, G. J. Miller, J. E. Warren, D. Antypov, F. Corà, B. Slater, M. R. Prestly, C. Martí-Gastaldo and M. J. Rosseinsky, Chemical and Structural Stability of Zirconium-based Metal–Organic Frameworks with Large Three-Dimensional Pores by Linker Engineering, *Angew. Chem., Int. Ed.* **2015**, *54*, 221-226.

35 K. S. Park, Z. Ni, A. P. Côté, J. Y. Choi, R. D. Huang, F. J. Uribe-Romo, H. K. Chae, M. O'Keeffe and O. M. Yaghi, Exceptional chemical and thermal stability of zeolitic imidazolate frameworks, *Proc. Natl. Acad. Sci. U. S. A.* **2006**, *103*, 10186-10191.

36 R. Banerjee, A. Phan, B. Wang, C. Knobler, H. Furukawa, M. O'Keeffe and O. M. Yaghi, High-throughput synthesis of zeolitic imidazolate frameworks and application to CO2 capture, *Science* **2008**, *319*, 939-943.

37 A. Phan, C. J. Doonan, F. J. Uribe-Romo, C. B. Knobler, M. O'Keeffe and O. M. Yaghi, Synthesis, structure, and carbon dioxide capture properties of zeolitic imidazolate frameworks, *Acc. Chem. Res.* **2010**, *43*, 58-67.

38 V. Colombo, S. Galli, H. J. Choi, G. D. Han, A. Maspero, G. Palmisano, N. Masciocchi and J. R. Long, High thermal and chemical stability in pyrazolate-bridged metal-organic frameworks with exposed metal sites, *Chem. Sci.* **2011**, *2*, 1311-1319.

39 P. S. Nugent, V. L. Rhodus, T. Pham, K. Forrest, L. Wojtas, B. Space and M. J. Zaworotko, A Robust Molecular Porous Material with High CO2 Uptake and Selectivity, *J. Am. Chem. Soc.* **2013**, *135*, 10950-10953.

40 P. Nugent, Y. Belmabkhout, S. D. Burd, A. J. Cairns, R. Luebke, K. Forrest, T. Pham, S. Q. Ma, B. Space, L. Wojtas, M. Eddaoudi and M. J. Zaworotko, Porous materials with optimal adsorption thermodynamics and kinetics for CO_2 separation, *Nature* **2013**, *495*, 80-84.

41 T. Loiseau, C. Serre, C. Huguenard, G. Fink, F. Taulelle, M. Henry, T. Bataille and G. Férey, A rationale for the large breathing of the porous aluminum terephthalate (MIL-53) upon hydration, *Chem. -Eur. J.* **2004**, *10*, 1373-1382.

42 P. Horcajada, S. Surblé, C. Serre, D. Y. Hong, Y. K. Seo, J. S. Chang, J. M. Grenèche, I. Margiolaki and G. Férey, Synthesis and catalytic properties of MIL-100(Fe), an iron(III) carboxylate with large pores, *Chem. Commun.* **2007**, 2820-2822.

43 W. Zhang, Y. Hu, J. Ge, H.-L. Jiang and S.-H. Yu, A Facile and General Coating Approach to Moisture/Water-Resistant Metal–Organic Frameworks with Intact Porosity, *J. Am. Chem. Soc.* **2014**, *136*, 16978-16981.

44 J. B. DeCoste, G. W. Peterson, H. Jasuja, T. G. Glover, Y.-g. Huang and K. S. Walton, Stability and degradation mechanisms of metal-organic frameworks containing the Zr6O4(OH)4 secondary building unit, *J. Mater. Chem. A* **2013**, *1*, 5642-5650.

45 C. G. Piscopo, A. Polyzoidis, M. Schwarzer and S. Loebbecke, Stability of UiO-66 under acidic treatment: Opportunities and limitations for post-synthetic modifications, *Micropor. Mesopor. Mat.* **2015**, *208*, 30-35.

46 Web of Science, http://apps.webofknowledge.com/WOS_GeneralSearch_input.do?product=WOS&search_mode=GeneralSearch&SID=T1AQWjAWVPW9otFXizV&preferencesSaved=.

47 S. Jakobsen, D. Gianolio, D. S. Wragg, M. H. Nilsen, H. Emerich, S. Bordiga, C. Lamberti, U. Olsbye, M. Tilset and K. P. Lillerud, Structural determination of a highly stable metal-organic framework with possible application to interim radioactive waste scavenging: Hf-UiO-66, *Phys. Rev. B* **2012**, *86*, 125429.

48 C. Orellana-Tavra, E. F. Baxter, T. Tian, T. D. Bennett, N. K. H. Slater, A. K. Cheetham and D. Fairen-Jimenez, Amorphous metal-organic frameworks for drug delivery, *Chem. Commun.* **2015**, *51*, 13878-13881.

49 M. Dan-Hardi, C. Serre, T. Frot, L. Rozes, G. Maurin, C. Sanchez and G. Ferey, A New Photoactive Crystalline Highly Porous Titanium(IV) Dicarboxylate, *J. Am. Chem. Soc.* **2009**, *131*, 10857-10859.

50 Y. Fu, D. Sun, Y. Chen, R. Huang, Z. Ding, X. Fu and Z. Li, An Amine-Functionalized Titanium Metal–Organic Framework Photocatalyst with Visible-Light-Induced Activity for CO2 Reduction, *Angew. Chem., Int. Ed.* **2012**, *51*, 3364-3367.

51 M. H. Beyzavi, R. C. Klet, S. Tussupbayev, J. Borycz, N. A. Vermeulen, C. J. Cramer, J. F. Stoddart, J. T. Hupp and O. K. Farha, A Hafnium-Based Metal–Organic Framework as an Efficient and Multifunctional Catalyst for Facile CO2 Fixation and Regioselective and Enantioretentive Epoxide Activation, *J. Am. Chem. Soc.* **2014**, *136*, 15861-15864.

52 L. Li, K. Wang, H. Huang, Q. Yang, Y. Zhang, S. Wang, P. Wu, L. Lan, D. Liu and C. Zhong, Synthesis of exceptional stable Hf-based metal-organic frameworks: characterization, stability and CO_2 adsorption performance, *CIESC J.* **2014**, *65*, 1706-1715.

53 K. E. deKrafft, W. S. Boyle, L. M. Burk, O. Z. Zhou and W. Lin, Zr- and Hf-based nanoscale metal-organic frameworks as contrast agents for computed tomography, *J. Mater. Chem.* **2012**, *22*, 18139-18144.

54 D. Feng, H.-L. Jiang, Y.-P. Chen, Z.-Y. Gu, Z. Wei and H.-C. Zhou, Metal–Organic Frameworks Based on Previously Unknown Zr8/Hf8 Cubic Clusters, *Inorg. Chem.* **2013**, *52*, 12661-12667.

55 V. Bon, I. Senkovska, I. A. Baburin and S. Kaskel, Zr- and Hf-Based Metal–Organic Frameworks: Tracking Down the Polymorphism, *Cryst. Growth Des.* **2013**, *13*, 1231-1237.

56 P. Xydias, I. Spanopoulos, E. Klontzas, G. E. Froudakis and P. N. Trikalitis, Drastic Enhancement of the CO2 Adsorption Properties in Sulfone-Functionalized Zr- and Hf-UiO-67 MOFs with Hierarchical Mesopores, *Inorg. Chem.* **2014**, *53*, 679-681.

57 R. J. Marshall, S. L. Griffin, C. Wilson and R. S. Forgan, Single-Crystal to Single-Crystal Mechanical Contraction of Metal–Organic Frameworks through Stereoselective Postsynthetic Bromination, *J. Am. Chem. Soc.* **2015**, *137*, 9527-9530.

58 M. Lammert, M. T. Wharmby, S. Smolders, B. Bueken, A. Lieb, K. A. Lomachenko, D. D. Vos and N. Stock, Cerium-based metal organic frameworks with UiO-66 architecture: synthesis, properties and redox catalytic activity, *Chem. Commun.* **2015**, *51*, 12578-12581.

59 C. Falaise, C. Volkringer, J.-F. Vigier, N. Henry, A. Beaurain and T. Loiseau, Three-Dimensional MOF-Type Architectures with Tetravalent Uranium Hexanuclear Motifs (U6O8), *Chem. -Eur. J.* **2013**, *19*, 5324-5331.

60 C. Falaise, A. Assen, I. Mihalcea, C. Volkringer, A. Mesbah, N. Dacheux and T. Loiseau, Coordination polymers of uranium(iv) terephthalates, *Dalton Trans.* **2015**, *44*, 2639-2649.

61 C. Falaise, J.-S. Charles, C. Volkringer and T. Loiseau, Thorium Terephthalates Coordination Polymers Synthesized in

Solvothermal DMF/H2O System, *Inorg. Chem.* **2015**, *54*, 2235-2242.

62 G. Wißmann, A. Schaate, S. Lilienthal, I. Bremer, A. M. Schneider and P. Behrens, Modulated synthesis of Zr-fumarate MOF, *Micropor. Mesopor. Mat.* **2012**, *152*, 64-70.

63 J. Aguilera-Sigalat, A. Fox-Charles and D. Bradshaw, Direct photo-hydroxylation of the Zr-based framework UiO-66, *Chem. Commun.* **2014**, *50*, 15453-15456.

64 L. Valenzano, B. Civalleri, S. Chavan, S. Bordiga, M. H. Nilsen, S. Jakobsen, K. P. Lillerud and C. Lamberti, Disclosing the Complex Structure of UiO-66 Metal Organic Framework: A Synergic Combination of Experiment and Theory, *Chem. Mater.* **2011**, *23*, 1700-1718.

65 M. J. Katz, Z. J. Brown, Y. J. Colón, P. W. Siu, K. A. Scheidt, R. Q. Snurr, J. T. Hupp and O. K. Farha, A facile synthesis of UiO-66, UiO-67 and their derivatives, *Chem. Commun.* **2013**, *49*, 9449-9451.

66 Z. Hu, S. Faucher, Y. Zhuo, Y. Sun, S. Wang and D. Zhao, Combination of Optimization and Metalated-Ligand Exchange: An Effective Approach to Functionalize UiO-66(Zr) MOFs for CO_2 Separation, *Chem. -Eur. J.* **2015**, 10.1002/chem.201503078.

67 M. J. Cliffe, W. Wan, X. Zou, P. A. Chater, A. K. Kleppe, M. G. Tucker, H. Wilhelm, N. P. Funnell, F.-X. Coudert and A. L. Goodwin, Correlated defect nanoregions in a metal–organic framework, *Nat. Commun.* **2014**, *5*, 4176.

68 Z. Hu, A. Nalaparaju, Y. Peng, J. Jiang and D. Zhao, UiO-66(Hf)-Type Metal-Organic Frameworks for Optimal Carbon Dioxide Capture, to be submitted.

69 J. R. Li, J. Sculley and H. C. Zhou, Metal-organic frameworks for separations, *Chem. Rev.* **2012**, *112*, 869-932.

70 M. Kim and S. M. Cohen, Discovery, development, and functionalization of Zr(IV)-based metal-organic frameworks, *CrystEngComm* **2012**, *14*, 4096-4104.

71 A. Buragohain and S. Biswas, Improved Synthesis of a Zirconium(IV) Muconate Metal–Organic Framework: Characterization, Stability and Gas Sorption Properties, *Eur. J. Inorg. Chem.* **2015**, *2015*, 2463-2468.

72 H. Reinsch, B. Bueken, F. Vermoortele, I. Stassen, A. Lieb, K.-P. Lillerud and D. De Vos, Green synthesis of zirconium-MOFs, *CrystEngComm* **2015**, *17*, 4070-4074.

73 M. Taddei, P. V. Dau, S. M. Cohen, M. Ranocchiari, J. A. van Bokhoven, F. Costantino, S. Sabatini and R. Vivani, Efficient microwave assisted synthesis of metal-organic framework UiO-66: optimization and scale up, *Dalton Trans.* **2015**, *44*, 14019-14026.

74 A. Schaate, P. Roy, A. Godt, J. Lippke, F. Waltz, M. Wiebcke and P. Behrens, Modulated synthesis of Zr-based metal-organic frameworks: from nano to single crystals, *Chem. -Eur. J.* **2011**, *17*, 6643-6651.

75 A. Schaate, P. Roy, T. Preusse, S. J. Lohmeier, A. Godt and P. Behrens, Porous Interpenetrated Zirconium-Organic Frameworks (PIZOFs): A Chemically Versatile Family of Metal-Organic Frameworks, *Chem. -Eur. J.* **2011**, *17*, 9320-9325.

76 Y. Zhou and H. C. Zeng, Simultaneous Synthesis and Assembly of Noble Metal Nanoclusters with Variable Micellar Templates, *J. Am. Chem. Soc.* **2014**, *136*, 13805-13817.

77 J. B. Hubbard, V. Silin and A. L. Plant, Self assembly driven by hydrophobic interactions at alkanethiol monolayers: mechanism of formation of hybrid bilayer membranes, *Biophys. Chem.* **1998**, *75*, 163-176.

78 G. M. Whitesides and M. Boncheva, Beyond molecules: Self-assembly of mesoscopic and macroscopic components, *Proc. Natl. Acad. Sci. U. S. A.* **2002**, *99*, 4769-4774.

79 C. Housecroft and A. G. Sharpe, *Inorganic Chemistry*, Prentice Hall, 2012.

80 C. A. Trickett, K. J. Gagnon, S. Lee, F. Gándara, H.-B. Bürgi and O. M. Yaghi, Definitive Molecular Level Characterization of Defects in UiO-66 Crystals, *Angew. Chem., Int. Ed.* **2015**, *54*, 11162-11167.

81 S. Biswas, J. Zhang, Z. B. Li, Y. Y. Liu, M. Grzywa, L. X. Sun, D. Volkmer and P. Van der Voort, Enhanced selectivity of CO_2 over CH_4 in sulphonate-, carboxylate- and iodo-functionalized UiO-66 frameworks, *Dalton Trans.* **2013**, *42*, 4730-4737.

82 P. S. Bárcia, D. Guimarães, P. A. P. Mendes, J. A. C. Silva, V. Guillerm, H. Chevreau, C. Serre and A. E. Rodrigues, Reverse shape selectivity in the adsorption of hexane and xylene isomers in MOF UiO-66, *Micropor. Mesopor. Mat.* **2011**, *139*, 67-73.

83 Q. Zhao, W. Yuan, J. Liang and J. Li, Synthesis and hydrogen storage studies of metal–organic framework UiO-66, *Int. J. Hydrogen Energy* **2013**, *38*, 13104-13109.

84 F. Vermoortele, B. Bueken, G. Le Bars, B. Van de Voorde, M. Vandichel, K. Houthoofd, A. Vimont, M. Daturi, M. Waroquier, V. Van Speybroeck, C. Kirschhock and D. E. De Vos, Synthesis Modulation as a Tool To Increase the Catalytic Activity of Metal–Organic Frameworks: The Unique Case of UiO-66(Zr), *J. Am. Chem. Soc.* **2013**, *135*, 11465-11468.

85 F. Ragon, P. Horcajada, H. Chevreau, Y. K. Hwang, U.-H. Lee, S. R. Miller, T. Devic, J.-S. Chang and C. Serre, In Situ Energy-Dispersive X-ray Diffraction for the Synthesis Optimization and Scale-up of the Porous Zirconium Terephthalate UiO-66, *Inorg. Chem.* **2014**, *53*, 2491-2500.

86 J. Ren, H. W. Langmi, B. C. North, M. Mathe and D. Bessarabov, Modulated synthesis of zirconium-metal organic framework (Zr-MOF) for hydrogen storage applications, *Int. J. Hydrogen Energy* **2014**, *39*, 890-895.

87 B. Van de Voorde, I. Stassen, B. Bueken, F. Vermoortele, D. De Vos, R. Ameloot, J.-C. Tan and T. D. Bennett, Improving the mechanical stability of zirconium-based metal-organic frameworks by incorporation of acidic modulators, *J. Mater. Chem. A* **2015**, *3*, 1737-1742.

88 M. Sk, S. Bhowal and S. Biswas, Synthesis, Characterization, Stability, and Gas Adsorption Characteristics of a Highly Stable Zirconium Mesaconate Framework Material, *Eur. J. Inorg. Chem.* **2015**, *2015*, 3317-3322.

89 G. Zahn, H. A. Schulze, J. Lippke, S. König, U. Sazama, M. Fröba and P. Behrens, A water-born Zr-based porous coordination polymer: Modulated synthesis of Zr-fumarate MOF, *Micropor. Mesopor. Mat.* **2015**, *203*, 186-194.

90 M. Ganesh, P. Hemalatha, M. M. Peng, W. S. Cha and H. T. Jang, Zr-Fumarate MOF a Novel CO2-Adsorbing Material: Synthesis and Characterization, *Aerosol Air Qual. Res.* **2014**, *14*, 1605-1612.

91 Z. Hu, K. Zhang, M. Zhang, Z. Guo, J. Jiang and D. Zhao, A Combinatorial Approach towards Water-Stable Metal-Organic Frameworks for Highly Efficient Carbon Dioxide Separation, *ChemSusChem* **2014**, *7*, 2791-2795.

92 A. D. Wiersum, E. Soubeyrand-Lenoir, Q. Y. Yang, B. Moulin, V. Guillerm, M. Ben Yahia, S. Bourrelly, A. Vimont, S. Miller, C. Vagner, M. Daturi, G. Clet, C. Serre, G. Maurin and P. L. Llewellyn, An Evaluation of UiO-66 for Gas-Based Applications, *Chem. Asian J.* **2011**, *6*, 3270-3280.

93 Q. Y. Yang, A. D. Wiersum, P. L. Llewellyn, V. Guillerm, C. Serred and G. Maurin, Functionalizing porous zirconium terephthalate

UiO-66(Zr) for natural gas upgrading: a computational exploration, *Chem. Commun.* **2011**, *47*, 9603-9605.

94 G. E. Cmarik, M. Kim, S. M. Cohen and K. S. Walton, Tuning the Adsorption Properties of UiO-66 via Ligand Functionalization, *Langmuir* **2012**, *28*, 15606-15613.

95 M. Kandiah, M. H. Nilsen, S. Usseglio, S. Jakobsen, U. Olsbye, M. Tilset, C. Larabi, E. A. Quadrelli, F. Bonino and K. P. Lillerud, Synthesis and Stability of Tagged UiO-66 Zr-MOFs, *Chem. Mater.* **2010**, *22*, 6632-6640.

96 H. Jasuja, G. W. Peterson, J. B. Decoste, M. A. Browe and K. S. Walton, Evaluation of MOFs for air purification and air quality control applications: Ammonia removal from air, *Chem. Eng. Sci.* **2015**, *124*, 118-124.

97 S. Biswas and P. Van Der Voort, A General Strategy for the Synthesis of Functionalised UiO-66 Frameworks: Characterisation, Stability and CO2 Adsorption Properties, *Eur. J. Inorg. Chem.* **2013**, *2013*, 2154-2160.

98 D. Cunha, C. Gaudin, I. Colinet, P. Horcajada, G. Maurin and C. Serre, Rationalization of the entrapping of bioactive molecules into a series of functionalized porous zirconium terephthalate MOFs, *J. Mater. Chem. B* **2013**, *1*, 1101-1108.

99 Y. Huang, W. Qin, Z. Li and Y. Li, Enhanced stability and CO2 affinity of a UiO-66 type metal-organic framework decorated with dimethyl groups, *Dalton Trans.* **2012**, *41*, 9283-9285.

100 H. Jasuja, J. Zang, D. S. Sholl and K. S. Walton, Rational Tuning of Water Vapor and CO_2 Adsorption in Highly Stable Zr-Based MOFs, *Journal of Physical Chemistry C* **2012**, *116*, 23526-23532.

101 J. Juan-Alcañiz, R. Gielisse, A. B. Lago, E. V. Ramos-Fernandez, P. Serra-Crespo, T. Devic, N. Guillou, C. Serre, F. Kapteijn and J. Gascon, Towards acid MOFs-catalytic performance of sulfonic acid functionalized architectures, *Catal. Sci. Technol.* **2013**, *3*, 2311-2318.

102 Z. Hu, Y. Peng, Z. Kang, Y. Qian and D. Zhao, A Modulated Hydrothermal (MHT) Approach for the Facile Synthesis of UiO-66-Type MOFs, *Inorg. Chem.* **2015**, *54*, 4862-4868.

103 W. J. Phang, H. Jo, W. R. Lee, J. H. Song, K. Yoo, B. Kim and C. S. Hong, Superprotonic Conductivity of a UiO-66 Framework Functionalized with Sulfonic Acid Groups by Facile Postsynthetic Oxidation, *Angew. Chem., Int. Ed.* **2015**, *54*, 5142-5146.

104 H. Jasuja and K. S. Walton, Experimental Study of CO2, CH4, and Water Vapor Adsorption on a Dimethyl-Functionalized UiO-66 Framework, *The Journal of Physical Chemistry C* **2013**, *117*, 7062-7068.

105 Z. Hu, M. Khurana, Y. H. Seah, M. Zhang, Z. Guo and D. Zhao, Ionized Zr-MOFs for highly efficient post-combustion CO_2 capture, *Chem. Eng. Sci.* **2015**, *124*, 61-69.

106 Q. Yang, S. Vaesen, F. Ragon, A. D. Wiersum, D. Wu, A. Lago, T. Devic, C. Martineau, F. Taulelle, P. L. Llewellyn, H. Jobic, C. Zhong, C. Serre, G. De Weireld and G. Maurin, A Water Stable Metal–Organic Framework with Optimal Features for CO_2 Capture, *Angew. Chem., Int. Ed.* **2013**, *52*, 10316-10320.

107 J. E. Mondloch, O. Karagiaridi, O. K. Farha and J. T. Hupp, Activation of metal-organic framework materials, *CrystEngComm* **2013**, *15*, 9258-9264.

108 T. M. McDonald, E. D. Bloch and J. R. Long, Rapidly assessing the activation conditions and porosity of metal-organic frameworks using thermogravimetric analysis, *Chem. Commun.* **2015**, *51*, 4985-4988.

109 E. Alvarez, N. Guillou, C. Martineau, B. Bueken, B. Van de Voorde, C. Le Guillouzer, P. Fabry, F. Nouar, F. Taulelle, D. de Vos, J.-S. Chang, K. H. Cho, N. Ramsahye, T. Devic, M. Daturi, G. Maurin and C. Serre, The Structure of the Aluminum Fumarate Metal–Organic Framework A520, *Angew. Chem., Int. Ed.* **2015**, *54*, 3664-3668.

110 V. Guillerm, S. Gross, C. Serre, T. Devic, M. Bauer and G. Férey, A zirconium methacrylate oxocluster as precursor for the low-temperature synthesis of porous zirconium(IV) dicarboxylates, *Chem. Commun.* **2010**, *46*, 767-769.

111 M. E. Davis and R. J. Davis, *Fundamentals of chemical reaction engineering*, McGraw-Hill Higher Education, New York, 2003.

112 G. F. Froment, K. B. Bischoff and J. D. Wilde, *Chemical Reactor Analysis and Design*, Wiley, 2010.

113 S. Waitschat, M. T. Wharmby and N. Stock, Flow-synthesis of carboxylate and phosphonate based metal-organic frameworks under non-solvothermal reaction conditions, *Dalton Trans.* **2015**, *44*, 11235-11240.

114 M. P. Batten, M. Rubio-Martinez, T. Hadley, K.-C. Carey, K.-S. Lim, A. Polyzos and M. R. Hill, Continuous flow production of metal-organic frameworks, *Current Opinion in Chemical Engineering* **2015**, *8*, 55-59.

115 S. Tai, W. Zhang, J. Zhang, G. Luo, Y. Jia, M. Deng and Y. Ling, Facile Preparation of UiO-66 Nanoparticles with Tunable Sizes in a Continuous Flow Microreactor and Its Application in Drug Delivery, *Micropor. Mesopor. Mat.* **2015**, 10.1016/j.micromeso.2015.1008.1037.

116 M. Gimeno-Fabra, A. S. Munn, L. A. Stevens, T. C. Drage, D. M. Grant, R. J. Kashtiban, J. Sloan, E. Lester and R. I. Walton, Instant MOFs: continuous synthesis of metal-organic frameworks by rapid solvent mixing, *Chem. Commun.* **2012**, *48*, 10642-10644.

117 P. M. Schoenecker, G. A. Belancik, B. E. Grabicka and K. S. Walton, Kinetics study and crystallization process design for scale-up of UiO-66-NH2 synthesis, *AIChE J.* **2013**, *59*, 1255-1262.

118 K.-J. Kim, Y. J. Li, P. B. Kreider, C.-H. Chang, N. Wannenmacher, P. K. Thallapally and H.-G. Ahn, High-rate synthesis of Cu-BTC metal-organic frameworks, *Chem. Commun.* **2013**, *49*, 11518-11520.

119 M. Rubio-Martinez, M. P. Batten, A. Polyzos, K.-C. Carey, J. I. Mardel, K.-S. Lim and M. R. Hill, Versatile, High Quality and Scalable Continuous Flow Production of Metal-Organic Frameworks, *Sci. Rep.* **2014**, *4*, 5443.

120 S.-N. Kim, Y.-R. Lee, S.-H. Hong, M.-S. Jang and W.-S. Ahn, Pilot-scale synthesis of a zirconium-benzenedicarboxylate UiO-66 for CO2 adsorption and catalysis, *Catal. Today* **2015**, *245*, 54-60.

121 M. Faustini, J. Kim, G.-Y. Jeong, J. Y. Kim, H. R. Moon, W.-S. Ahn and D.-P. Kim, Microfluidic Approach toward Continuous and Ultrafast Synthesis of Metal–Organic Framework Crystals and Hetero Structures in Confined Microdroplets, *J. Am. Chem. Soc.* **2013**, *135*, 14619-14626.

122 G. F. Christopher and S. L. Anna, Microfluidic methods for generating continuous droplet streams, *J. Phys. D: Appl. Phys.* **2007**, *40*, R319.

123 C. N. Baroud, F. Gallaire and R. Dangla, Dynamics of microfluidic droplets, *Lab Chip* **2010**, *10*, 2032-2045.

124 S. Sharma, R. A. Maurya, K.-I. Min, G.-Y. Jeong and D.-P. Kim, Odorless Isocyanide Chemistry: An Integrated Microfluidic System for a Multistep Reaction Sequence, *Angew. Chem., Int. Ed.* **2013**, *52*, 7564-7568.

125 R. Ameloot, F. Vermoortele, W. Vanhove, M. B. J. Roeffaers, B. F. Sels and D. E. De Vos, Interfacial synthesis of hollow metal–organic framework capsules demonstrating selective permeability, *Nat. Chem.* **2011**, *3*, 382-387.

126 L. Paseta, B. Seoane, D. Julve, V. Sebastián, C. Téllez and J. Coronas, Accelerating the Controlled Synthesis of Metal–Organic

Frameworks by a Microfluidic Approach: A Nanoliter Continuous Reactor, *ACS Appl. Mater. Inter.* **2013**, *5*, 9405-9410.

127 B. Chen, M. Eddaoudi, T. M. Reineke, J. W. Kampf, M. O'Keeffe and O. M. Yaghi, Cu2(ATC)·6H2O: Design of Open Metal Sites in Porous Metal–Organic Crystals (ATC: 1,3,5,7-Adamantane Tetracarboxylate), *J. Am. Chem. Soc.* **2000**, *122*, 11559-11560.

128 H. L. Li, C. E. Davis, T. L. Groy, D. G. Kelley and O. M. Yaghi, Coordinatively unsaturated metal centers in the extended porous framework of Zn-3(BDC)(3).6CH(3)OH (BDC=1,4-benzenedicarboxylate), *J. Am. Chem. Soc.* **1998**, *120*, 2186-2187.

129 Y. Liu, H. Kabbour, C. M. Brown, D. A. Neumann and C. C. Ahn, Increasing the density of adsorbed hydrogen with coordinatively unsaturated metal centers in metal-organic frameworks, *Langmuir* **2008**, *24*, 4772-4777.

130 J. Jiang and O. M. Yaghi, Brønsted Acidity in Metal–Organic Frameworks, *Chem. Rev.* **2015**, *115*, 6966-6997.

131 M. L. Foo, S. Horike, T. Fukushima, Y. Hijikata, Y. Kubota, M. Takata and S. Kitagawa, Ligand-based solid solution approach to stabilisation of sulphonic acid groups in porous coordination polymer $Zr_6O_4(OH)_4(BDC)_6$ (UiO-66), *Dalton Trans.* **2012**, *41*, 13791-13794.

132 M. G. Goesten, J. Juan-Alcañiz, E. V. Ramos-Fernandez, K. B. S. S. Gupta, E. Stavitski, H. van Bekkum, J. Gascon and F. Kapteijn, Sulfation of metal-organic frameworks: Opportunities for acid catalysis and proton conductivity, *J. Catal.* **2011**, *281*, 177-187.

133 K.-K. Yee, N. Reimer, J. Liu, S.-Y. Cheng, S.-M. Yiu, J. Weber, N. Stock and Z. Xu, Effective Mercury Sorption by Thiol-Laced Metal–Organic Frameworks: in Strong Acid and the Vapor Phase, *J. Am. Chem. Soc.* **2013**, *135*, 7795-7798.

134 W. Morris, W. E. Briley, E. Auyeung, M. D. Cabezas and C. A. Mirkin, Nucleic Acid–Metal Organic Framework (MOF) Nanoparticle Conjugates, *J. Am. Chem. Soc.* **2014**, *136*, 7261-7264.

135 D. J. Lun, G. I. N. Waterhouse and S. G. Telfer, A General Thermolabile Protecting Group Strategy for Organocatalytic Metal–Organic Frameworks, *J. Am. Chem. Soc.* **2011**, *133*, 5806-5809.

136 J. Bonnefoy, A. Legrand, E. A. Quadrelli, J. Canivet and D. Farrusseng, Enantiopure Peptide-Functionalized Metal-Organic Frameworks, *J. Am. Chem. Soc.* **2015**, *137*, 9409-9416.

137 K. Sumida, D. L. Rogow, J. A. Mason, T. M. McDonald, E. D. Bloch, Z. R. Herm, T. H. Bae and J. R. Long, Carbon dioxide capture in metal-organic frameworks, *Chem. Rev.* **2012**, *112*, 724-781.

138 J. Chun, S. Kang, N. Park, E. J. Park, X. Jin, K.-D. Kim, H. O. Seo, S. M. Lee, H. J. Kim, W. H. Kwon, Y.-K. Park, J. M. Kim, Y. D. Kim and S. U. Son, Metal–Organic Framework@Microporous Organic Network: Hydrophobic Adsorbents with a Crystalline Inner Porosity, *J. Am. Chem. Soc.* **2014**, *136*, 6786-6789.

139 S. Chavan, J. G. Vitillo, M. J. Uddin, F. Bonino, C. Lamberti, E. Groppo, K.-P. Lillerud and S. Bordiga, Functionalization of UiO-66 Metal–Organic Framework and Highly Cross-Linked Polystyrene with Cr(CO)3: In Situ Formation, Stability, and Photoreactivity, *Chem. Mater.* **2010**, *22*, 4602-4611.

140 M. Kandiah, S. Usseglio, S. Svelle, U. Olsbye, K. P. Lillerud and M. Tilset, Post-synthetic modification of the metal-organic framework compound UiO-66, *J. Mater. Chem.* **2010**, *20*, 9848-9851.

141 S. Nagata, K. Kokado and K. Sada, Metal-organic framework tethering PNIPAM for ON-OFF controlled release in solution, *Chem. Commun.* **2015**, *51*, 8614-8617.

142 M. Zha, J. Liu, Y.-L. Wong and Z. Xu, Extraction of palladium from nuclear waste-like acidic solutions by a metal-organic framework with sulfur and alkene functions, *J. Mater. Chem. A* **2015**, *3*, 3928-3934.

143 R. J. White, R. Luque, V. L. Budarin, J. H. Clark and D. J. Macquarrie, Supported metal nanoparticles on porous materials. Methods and applications, *Chem. Soc. Rev.* **2009**, *38*, 481-494.

144 K. Na, K. M. Choi, O. M. Yaghi and G. A. Somorjai, Metal Nanocrystals Embedded in Single Nanocrystals of MOFs Give Unusual Selectivity as Heterogeneous Catalysts, *Nano Lett.* **2014**, *14*, 5979-5983.

145 K. M. Choi, K. Na, G. A. Somorjai and O. M. Yaghi, Chemical Environment Control and Enhanced Catalytic Performance of Platinum Nanoparticles Embedded in Nanocrystalline Metal-Organic Frameworks, *J. Am. Chem. Soc.* **2015**, *137*, 7810-7816.

146 S. Devautour-Vinot, C. Martineau, S. Diaby, M. Ben-Yahia, S. Miller, C. Serre, P. Horcajada, D. Cunha, F. Taulelle and G. Maurin, Caffeine Confinement into a Series of Functionalized Porous Zirconium MOFs: A Joint Experimental/Modeling Exploration, *The Journal of Physical Chemistry C* **2013**, *117*, 11694-11704.

147 N. T. T. Van, L. C. Loc, N. Tri and H. T. Cuong, Synthesis, characterisation, adsorption ability and activity of Cu,ZnO@UiO–66 in methanol synthesis, *International Journal of Nanotechnology* **2015**, *12*, 405-415.

148 Z. Sha and J. Wu, Enhanced visible-light photocatalytic performance of BiOBr/UiO-66(Zr) composite for dye degradation with the assistance of UiO-66, *RSC Adv.* **2015**, *5*, 39592-39600.

149 R. Ameloot, M. Aubrey, B. M. Wiers, A. P. Gómora-Figueroa, S. N. Patel, N. P. Balsara and J. R. Long, Ionic Conductivity in the Metal–Organic Framework UiO-66 by Dehydration and Insertion of Lithium tert-Butoxide, *Chem. -Eur. J.* **2013**, *19*, 5533-5536.

150 E. López-Maya, C. Montoro, L. M. Rodríguez-Albelo, S. D. Aznar Cervantes, A. A. Lozano-Pérez, J. L. Cenís, E. Barea and J. A. R. Navarro, Textile/Metal–Organic-Framework Composites as Self-Detoxifying Filters for Chemical-Warfare Agents, *Angew. Chem., Int. Ed.* **2015**, *54*, 6790-6794.

151 M. Pintado-Sierra, A. M. Rasero-Almansa, A. Corma, M. Iglesias and F. Sánchez, Bifunctional iridium-(2-aminoterephthalate)–Zr-MOF chemoselective catalyst for the synthesis of secondary amines by one-pot three-step cascade reaction, *J. Catal.* **2013**, *299*, 137-145.

152 Z. Sha, J. Sun, H. S. On Chan, S. Jaenicke and J. Wu, Bismuth tungstate incorporated zirconium metal-organic framework composite with enhanced visible-light photocatalytic performance, *RSC Adv.* **2014**, *4*, 64977-64984.

153 D. Yang, S. O. Odoh, T. C. Wang, O. K. Farha, J. T. Hupp, C. J. Cramer, L. Gagliardi and B. C. Gates, Metal–Organic Framework Nodes as Nearly Ideal Supports for Molecular Catalysts: NU-1000- and UiO-66-Supported Iridium Complexes, *J. Am. Chem. Soc.* **2015**, *137*, 7391-7396.

154 J. Wu, Y. Gao, W. Zhang, Y. Tan, A. Tang, Y. Men and B. Tang, Deep desulfurization by oxidation using an active ionic liquid-supported Zr metal–organic framework as catalyst, *Appl. Organometal. Chem.* **2015**, *29*, 96-100.

155 W. Zhang, G. Lu, C. Cui, Y. Liu, S. Li, W. Yan, C. Xing, Y. R. Chi, Y. Yang and F. Huo, A Family of Metal-Organic Frameworks Exhibiting Size-Selective Catalysis with Encapsulated Noble-Metal Nanoparticles, *Adv. Mater.* **2014**, *26*, 4056-4060.

156 Z. Guo, C. Xiao, R. V. Maligal-Ganesh, L. Zhou, T. W. Goh, X. Li, D. Tesfagaber, A. Thiel and W. Huang, Pt Nanoclusters Confined

within Metal–Organic Framework Cavities for Chemoselective Cinnamaldehyde Hydrogenation, *ACS Catal.* **2014**, *4*, 1340-1348.

157 X. Li, Z. Guo, C. Xiao, T. W. Goh, D. Tesfagaber and W. Huang, Tandem Catalysis by Palladium Nanoclusters Encapsulated in Metal–Organic Frameworks, *ACS Catal.* **2014**, *4*, 3490-3497.

158 H. Liu, L. Chang, L. Chen and Y. Li, In situ one-step synthesis of metal-organic framework encapsulated naked Pt nanoparticles without additional reductants, *J. Mater. Chem. A* **2015**, *3*, 8028-8033.

159 Z. Xu, L. Yang and C. Xu, Pt@UiO-66 Heterostructures for Highly Selective Detection of Hydrogen Peroxide with an Extended Linear Range, *Anal. Chem.* **2015**, *87*, 3438-3444.

160 R. Wu, X. Qian, K. Zhou, H. Liu, B. Yadian, J. Wei, H. Zhu and Y. Huang, Highly dispersed Au nanoparticles immobilized on Zr-based metal-organic frameworks as heterostructured catalyst for CO oxidation, *J. Mater. Chem. A* **2013**, *1*, 14294-14299.

161 K. Tulig and K. S. Walton, An alternative UiO-66 synthesis for HCl-sensitive nanoparticle encapsulation, *RSC Adv.* **2014**, *4*, 51080-51083.

162 K. Leus, P. Concepcion, M. Vandichel, M. Meledina, A. Grirrane, D. Esquivel, S. Turner, D. Poelman, M. Waroquier, V. Van Speybroeck, G. Van Tendeloo, H. Garcia and P. Van Der Voort, Au@UiO-66: a base free oxidation catalyst, *RSC Adv.* **2015**, *5*, 22334-22342.

163 Z. Sha, J. Sun, H. S. O. Chan, S. Jaenicke and J. Wu, Enhanced Photocatalytic Activity of the AgI/UiO-66(Zr) Composite for Rhodamine B Degradation under Visible-Light Irradiation, *ChemPlusChem* **2015**, *80*, 1321-1328.

164 Q. Yuan, D. Zhang, L. v. Haandel, F. Ye, T. Xue, E. J. M. Hensen and Y. Guan, Selective liquid phase hydrogenation of furfural to furfuryl alcohol by Ru/Zr-MOFs, *J. Mol. Catal. A* **2015**, *406*, 58-64.

165 E. Žunkovič, M. Mazaj, G. Mali, M. Rangus, T. Devic, C. Serre and N. Z. Logar, Structural study of Ni- or Mg-based complexes incorporated within UiO-66-NH2 framework and their impact on hydrogen sorption properties, *J. Solid. State Chem.* **2015**, *225*, 209-215.

166 Y. Luan, Y. Qi, H. Gao, R. S. Andriamitantsoa, N. Zheng and G. Wang, A general post-synthetic modification approach of amino-tagged metal-organic frameworks to access efficient catalysts for the Knoevenagel condensation reaction, *J. Mater. Chem. A* **2015**, *3*, 17320-17331.

167 J. Ye and J. K. Johnson, Design of Lewis Pair-Functionalized Metal Organic Frameworks for CO2 Hydrogenation, *ACS Catal.* **2015**, *5*, 2921-2928.

168 X.-L. Yang, L.-M. Qiao and W.-L. Dai, Phosphotungstic acid encapsulated in metal-organic framework UiO-66: An effective catalyst for the selective oxidation of cyclopentene to glutaraldehyde, *Micropor. Mesopor. Mat.* **2015**, *211*, 73-81.

169 C. H. Lau, R. Babarao and M. R. Hill, A route to drastic increase of CO_2 uptake in Zr metal organic framework UiO-66, *Chem. Commun.* **2013**, *49*, 3634-3636.

170 M. Kim, J. F. Cahill, H. Fei, K. A. Prather and S. M. Cohen, Postsynthetic Ligand and Cation Exchange in Robust Metal–Organic Frameworks, *J. Am. Chem. Soc.* **2012**, *134*, 18082-18088.

171 C. K. Brozek and M. Dincă, Ti3+-, V2+/3+-, Cr2+/3+-, Mn2+-, and Fe2+-Substituted MOF-5 and Redox Reactivity in Cr- and Fe-MOF-5, *J. Am. Chem. Soc.* **2013**, *135*, 12886-12891.

172 F. Nouar, M. I. Breeze, B. C. Campo, A. Vimont, G. Clet, M. Daturi, T. Devic, R. I. Walton and C. Serre, Tuning the properties of the UiO-66 metal organic framework by Ce substitution, *Chem. Commun.* **2015**, *51*, 14458-14461.

173 H. G. T. Nguyen, L. Mao, A. W. Peters, C. O. Audu, Z. J. Brown, O. K. Farha, J. T. Hupp and S. T. Nguyen, Comparative study of titanium-functionalized UiO-66: support effect on the oxidation of cyclohexene using hydrogen peroxide, *Catal. Sci. Technol.* **2015**, *5*, 4444-4451.

174 D. Sun, W. Liu, M. Qiu, Y. Zhang and Z. Li, Introduction of a mediator for enhancing photocatalytic performance via post-synthetic metal exchange in metal-organic frameworks (MOFs), *Chem. Commun.* **2015**, *51*, 2056-2059.

175 O. Karagiaridi, W. Bury, J. E. Mondloch, J. T. Hupp and O. K. Farha, Solvent-Assisted Linker Exchange: An Alternative to the De Novo Synthesis of Unattainable Metal–Organic Frameworks, *Angew. Chem., Int. Ed.* **2014**, *53*, 4530-4540.

176 S. M. Cohen, Modifying MOFs: new chemistry, new materials, *Chem. Sci.* **2010**, *1*, 32-36.

177 D. H. Hong and M. P. Suh, Enhancing CO_2 Separation Ability of a Metal-Organic Framework by Post-Synthetic Ligand Exchange with Flexible Aliphatic Carboxylates, *Chem. -Eur. J.* **2014**, *20*, 426-434.

178 G. Nickerl, I. Senkovska and S. Kaskel, Tetrazine functionalized zirconium MOF as an optical sensor for oxidizing gases, *Chem. Commun.* **2015**, *51*, 2280-2282.

179 M. Kim, J. F. Cahill, Y. Su, K. A. Prather and S. M. Cohen, Postsynthetic ligand exchange as a route to functionalization of ‘inert’metal–organic frameworks, *Chem. Sci.* **2012**, *3*, 126-130.

180 H. Fei, J. Shin, Y. S. Meng, M. Adelhardt, J. Sutter, K. Meyer and S. M. Cohen, Reusable Oxidation Catalysis Using Metal-Monocatecholato Species in a Robust Metal–Organic Framework, *J. Am. Chem. Soc.* **2014**, *136*, 4965-4973.

181 H. Fei, S. Pullen, A. Wagner, S. Ott and S. M. Cohen, Functionalization of robust Zr(iv)-based metal-organic framework films via a postsynthetic ligand exchange, *Chem. Commun.* **2015**, *51*, 66-69.

182 H. Fei and S. M. Cohen, Metalation of a Thiocatechol-Functionalized Zr(IV)-Based Metal–Organic Framework for Selective C–H Functionalization, *J. Am. Chem. Soc.* **2015**, *137*, 2191-2194.

183 S. Pullen, H. Fei, A. Orthaber, S. M. Cohen and S. Ott, Enhanced Photochemical Hydrogen Production by a Molecular Diiron Catalyst Incorporated into a Metal–Organic Framework, *J. Am. Chem. Soc.* **2013**, *135*, 16997-17003.

184 G. Odian, *Principles of Polymerization*, 2004.

185 F. Ragon, B. Campo, Q. Yang, C. Martineau, A. D. Wiersum, A. Lago, V. Guillerm, C. Hemsley, J. F. Eubank, M. Vishnuvarthan, F. Taulelle, P. Horcajada, A. Vimont, P. L. Llewellyn, M. Daturi, S. Devautour-Vinot, G. Maurin, C. Serre, T. Devic and G. Clet, Acid-functionalized UiO-66(Zr) MOFs and their evolution after intra-framework cross-linking: structural features and sorption properties, *J. Mater. Chem. A* **2015**, *3*, 3294-3309.

186 Z. Hu, F. Huo, Y. Zhang, C. Chen, K. Tu, H. Jiang and L.-Q. Wang, “Smart” Nanocarriers: A New Paradigm for Tumor Targeting Drug Delivery Systems, *Drug Deliv. Lett.* **2011**, *1*, 67-84.

187 S. M. Chavan, G. C. Shearer, S. Svelle, U. Olsbye, F. Bonino, J. Ethiraj, K. P. Lillerud and S. Bordiga, Synthesis and Characterization of Amine-Functionalized Mixed-Ligand Metal–Organic Frameworks of UiO-66 Topology, *Inorg. Chem.* **2014**, *53*, 9509-9515.

188 M. Kim, J. F. Cahill, K. A. Prather and S. M. Cohen, Postsynthetic modification at orthogonal reactive sites on mixed, bifunctional metal-organic frameworks, *Chem. Commun.* **2011**, *47*, 7629-7631.

189 H. Deng, C. J. Doonan, H. Furukawa, R. B. Ferreira, J. Towne, C. B. Knobler, B. Wang and O. M. Yaghi, Multiple Functional Groups of Varying Ratios in Metal-Organic Frameworks, *Science* **2010**, *327*, 846-850.

190 Z. Yin, Y.-L. Zhou, M.-H. Zeng and M. Kurmoo, The concept of mixed organic ligands in metal-organic frameworks: design, tuning and functions, *Dalton Trans.* **2015**, *44*, 5258-5275.

191 T. W. Goh, C. Xiao, R. V. Maligal-Ganesh, X. Li and W. Huang, Utilizing mixed-linker zirconium based metal-organic frameworks to enhance the visible light photocatalytic oxidation of alcohol, *Chem. Eng. Sci.* **2015**, *124*, 45-51.

192 Z. H. Rada, H. R. Abid, H. Sun and S. Wang, Bifunctionalized Metal Organic Frameworks, UiO-66-NO2-N (N = -NH2, -(OH)2, -(COOH)2), for Enhanced Adsorption and Selectivity of CO2 and N2, *Journal of Chemical & Engineering Data* **2015**, *60*, 2152-2161.

193 J. Ethiraj, E. Albanese, B. Civalleri, J. G. Vitillo, F. Bonino, S. Chavan, G. C. Shearer, K. P. Lillerud and S. Bordiga, Carbon Dioxide Adsorption in Amine-Functionalized Mixed-Ligand Metal–Organic Frameworks of UiO-66 Topology, *ChemSusChem* **2014**, *7*, 3382-3388.

194 I. Erucar, G. Yilmaz and S. Keskin, Recent Advances in Metal-Organic Framework-Based Mixed Matrix Membranes, *Chem. Asian J.* **2013**, *8*, 1692-1704.

195 H. B. T. Jeazet, C. Staudt and C. Janiak, Metal-organic frameworks in mixed-matrix membranes for gas separation, *Dalton Trans.* **2012**, *41*, 14003-14027.

196 B. Zornoza, C. Tellez, J. Coronas, J. Gascon and F. Kapteijn, Metal organic framework based mixed matrix membranes: An increasingly important field of research with a large application potential, *Micropor. Mesopor. Mat.* **2013**, *166*, 67-78.

197 B. Seoane, J. Coronas, I. Gascon, M. E. Benavides, O. Karvan, J. Caro, F. Kapteijn and J. Gascon, Metal-organic framework based mixed matrix membranes: a solution for highly efficient CO2 capture?, *Chem. Soc. Rev.* **2015**, *44*, 2421-2454.

198 S. Qiu, M. Xue and G. Zhu, Metal-organic framework membranes: from synthesis to separation application, *Chem. Soc. Rev.* **2014**, *43*, 6116-6140.

199 S. Hermes, F. Schröder, R. Chelmowski, C. Wöll and R. A. Fischer, Selective Nucleation and Growth of Metal–Organic Open Framework Thin Films on Patterned COOH/CF3-Terminated Self-Assembled Monolayers on Au(111), *J. Am. Chem. Soc.* **2005**, *127*, 13744-13745.

200 E. Biemmi, C. Scherb and T. Bein, Oriented Growth of the Metal Organic Framework Cu3(BTC)2(H2O)3·xH2O Tunable with Functionalized Self-Assembled Monolayers, *J. Am. Chem. Soc.* **2007**, *129*, 8054-8055.

201 C. Scherb, A. Schödel and T. Bein, Directing the Structure of Metal–Organic Frameworks by Oriented Surface Growth on an Organic Monolayer, *Angew. Chem., Int. Ed.* **2008**, *47*, 5777-5779.

202 H. Bux, F. Y. Liang, Y. S. Li, J. Cravillon, M. Wiebcke and J. Caro, Zeolitic Imidazolate Framework Membrane with Molecular Sieving Properties by Microwave-Assisted Solvothermal Synthesis, *J. Am. Chem. Soc.* **2009**, *131*, 16000-16001.

203 X. Liu, N. K. Demir, Z. Wu and K. Li, Highly Water-Stable Zirconium Metal–Organic Framework UiO-66 Membranes Supported on Alumina Hollow Fibers for Desalination, *J. Am. Chem. Soc.* **2015**, *137*, 6999-7002.

204 M. Miyamoto, S. Kohmura, H. Iwatsuka, Y. Oumi and S. Uemiya, In situ solvothermal growth of highly oriented Zr-based metal organic framework UiO-66 film with monocrystalline layer, *CrystEngComm* **2015**, *17*, 3422-3425.

205 I. Hod, W. Bury, D. M. Karlin, P. Deria, C.-W. Kung, M. J. Katz, M. So, B. Klahr, D. Jin, Y.-W. Chung, T. W. Odom, O. K. Farha and J. T. Hupp, Directed Growth of Electroactive Metal-Organic Framework Thin Films Using Electrophoretic Deposition, *Adv. Mater.* **2014**, *26*, 6295-6300.

206 I. Stassen, M. Styles, T. Van Assche, N. Campagnol, J. Fransaer, J. Denayer, J.-C. Tan, P. Falcaro, D. De Vos and R. Ameloot, Electrochemical Film Deposition of the Zirconium Metal–Organic Framework UiO-66 and Application in a Miniaturized Sorbent Trap, *Chem. Mater.* **2015**, *27*, 1801-1807.

207 O. G. Nik, X. Y. Chen and S. Kaliaguine, Functionalized metal organic framework-polyimide mixed matrix membranes for CO2/CH4 separation, *J. Membr. Sci.* **2012**, *413–414*, 48-61.

208 L. M. Robeson, The upper bound revisited, *J. Membr. Sci.* **2008**, *320*, 390-400.

209 L. M. Robeson, Correlation of separation factor versus permeability for polymeric membranes, *J. Membr. Sci.* **1991**, *62*, 165-185.

210 S. Kanehashi, G. Q. Chen, L. Ciddor, A. Chaffee and S. E. Kentish, The impact of water vapor on CO2 separation performance of mixed matrix membranes, *J. Membr. Sci.* **2015**, *492*, 471-477.

211 S. R. Venna, M. Lartey, T. Li, A. Spore, S. Kumar, H. B. Nulwala, D. R. Luebke, N. L. Rosi and E. Albenze, Fabrication of MMMs with improved gas separation properties using externally-functionalized MOF particles, *J. Mater. Chem. A* **2015**, *3*, 5014-5022.

212 S. J. D. Smith, B. P. Ladewig, A. J. Hill, C. H. Lau and M. R. Hill, Post-synthetic Ti Exchanged UiO-66 Metal-Organic Frameworks that Deliver Exceptional Gas Permeability in Mixed Matrix Membranes, *Sci. Rep.* **2015**, *5*.

213 M. S. Denny and S. M. Cohen, In Situ Modification of Metal–Organic Frameworks in Mixed-Matrix Membranes, *Angew. Chem., Int. Ed.* **2015**, *54*, 9029-9032.

214 Y. Zhang, X. Feng, H. Li, Y. Chen, J. Zhao, S. Wang, L. Wang and B. Wang, Photoinduced Postsynthetic Polymerization of a Metal–Organic Framework toward a Flexible Stand-Alone Membrane, *Angew. Chem., Int. Ed.* **2015**, *54*, 4259-4263.

215 P. St. Petkov, G. N. Vayssilov, J. Liu, O. Shekhah, Y. Wang, C. Wöll and T. Heine, Defects in MOFs: A Thorough Characterization, *ChemPhysChem* **2012**, *13*, 2025-2029.

216 Z. Fang, J. P. Dürholt, M. Kauer, W. Zhang, C. Lochenie, B. Jee, B. Albada, N. Metzler-Nolte, A. Pöppl, B. Weber, M. Muhler, Y. Wang, R. Schmid and R. A. Fischer, Structural Complexity in Metal-Organic Frameworks: Simultaneous Modification of Open Metal Sites and Hierarchical Porosity by Systematic Doping with Defective Linkers, *J. Am. Chem. Soc.* **2014**, *136*, 9627-9636.

217 D. A. Keen and A. L. Goodwin, The crystallography of correlated disorder, *Nature* **2015**, *521*, 303-309.

218 H. Wu, Y. S. Chua, V. Krungleviciute, M. Tyagi, P. Chen, T. Yildirim and W. Zhou, Unusual and Highly Tunable Missing-Linker Defects in Zirconium Metal-Organic Framework UiO-66 and Their Important Effects on Gas Adsorption, *J. Am. Chem. Soc.* **2013**, *135*, 10525-10532.

219 S. Øien, D. Wragg, H. Reinsch, S. Svelle, S. Bordiga, C. Lamberti and K. P. Lillerud, Detailed Structure Analysis of Atomic Positions and Defects in Zirconium Metal–Organic Frameworks, *Cryst. Growth Des.* **2014**, *14*, 5370-5372.

220 P. Ghosh, Y. J. Colon and R. Q. Snurr, Water adsorption in UiO-66: the importance of defects, *Chem. Commun.* **2014**, *50*, 11329-11331.

221 G. C. Shearer, S. Chavan, J. Ethiraj, J. G. Vitillo, S. Svelle, U. Olsbye, C. Lamberti, S. Bordiga and K. P. Lillerud, Tuned to Perfection: Ironing Out the Defects in Metal–Organic Framework UiO-66, *Chem. Mater.* **2014**, *26*, 4068-4071.
222 M. J. Cliffe, J. A. Hill, C. A. Murray, F.-X. Coudert and A. L. Goodwin, Defect-dependent colossal negative thermal expansion in UiO-66(Hf) metal-organic framework, *Phys. Chem. Chem. Phys.* **2015**, *17*, 11586-11592.
223 V. Bon, V. Senkovskyy, I. Senkovska and S. Kaskel, Zr(iv) and Hf(iv) based metal-organic frameworks with reo-topology, *Chem. Commun.* **2012**, *48*, 8407-8409.
224 M. Vandichel, J. Hajek, F. Vermoortele, M. Waroquier, D. E. De Vos and V. Van Speybroeck, Active site engineering in UiO-66 type metal-organic frameworks by intentional creation of defects: a theoretical rationalization, *CrystEngComm* **2015**, *17*, 395-406.
225 J. M. Taylor, S. Dekura, R. Ikeda and H. Kitagawa, Defect Control To Enhance Proton Conductivity in a Metal–Organic Framework, *Chem. Mater.* **2015**, *27*, 2286-2289.
226 J. M. Taylor, T. Komatsu, S. Dekura, K. Otsubo, M. Takata and H. Kitagawa, The Role of a Three Dimensionally Ordered Defect Sublattice on the Acidity of a Sulfonated Metal–Organic Framework, *J. Am. Chem. Soc.* **2015**, *137*, 11498-11506.