

# ChemComm

Chemical Communications

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: C. Rosales-Martínez, M. Assis, C. Castillo Blas and I. Abánades Lázaro, *Chem. Commun.*, 2024, DOI: 10.1039/D4CC02581D.



This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the [Information for Authors](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the [Ethical guidelines](#) still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.

**Data availability**

View Article Online  
DOI: 10.1039/D4CC02581D

Data for this article, including full characterisation, are available at Zenodo at [10.5281/zenodo.12625580].

Note to the editor: The files in the repository are currently restricted, as the manuscript has not been accepted yet. We will make them fully available at the time of publication if the manuscript is accepted.



## COMMUNICATION

## Tuning the electronic properties of Zr UiO-66 through defect-functionalised multivariate modulation.

Carmen Rosales-Martínez,<sup>a</sup> Marcelo Assis,<sup>b\*</sup> Celia Castillo-Blas,<sup>c\*</sup> Isabel Abánades Lázaro<sup>a\*</sup>Received 00th January 20xx,  
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

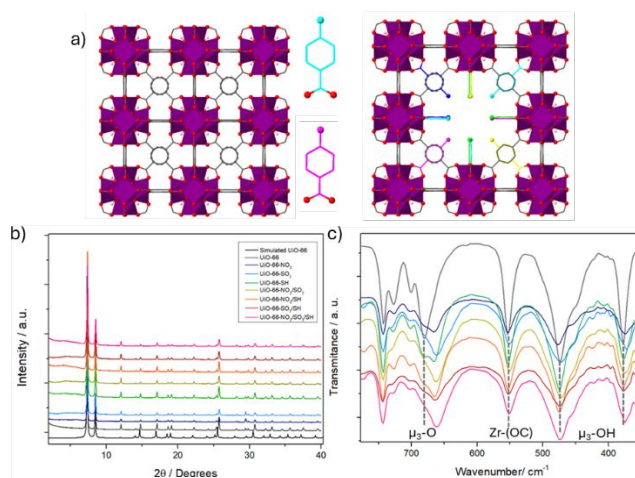
**The multivariate modulation of Metal-Organic Frameworks is presented as a valuable tool to introduce multiple functional units into UiO-66 while increasing its porosity. This manuscript encloses a comprehensive study using p-functionalised benzoate -NO<sub>2</sub>, -SO<sub>3</sub> and -SH modulators, rationalizing the defects introduced and their impact on properties.**

Modulated self-assembly of metal-organic frameworks (MOFs) has emerged as a valuable tool for modifying their properties.<sup>1,2</sup> Among the consequences of the introduction of modulators – organic ligands with fewer coordination sites than the linker, typically monotopic – stands the possibility of defect-functionalization.<sup>3,4</sup> Defect engineering has received significant attention as defects can tune the physical and electronic properties of materials.<sup>5,6</sup> In the same context, increasing the heterogeneity of MOFs through functionalization is also a hot topic with enhancement in diverse applications.<sup>7,8</sup> In this regard, multivariate chemistry provides the opportunity to introduce multiple functional groups, leading to pores with opposite dual properties and characteristics that are not the linear combination of their separate counterparts.<sup>9</sup> Combining these two hot topics through defect-engineering multivariate modulation of MOFs, represented in **Fig. 1a**, results in defect-functionalized multivariate structures with increased porosity and reactivity.<sup>4,10</sup> However, only a few examples are present in the literature, highlighting the need to further develop this concept.

Herein we present a comprehensive study of the defect multifunctionalisation of UiO-66 with p-functionalized benzoate (Benz) derivatives with -SO<sub>3</sub><sup>-</sup>, -NO<sub>2</sub> and -SH functionalised groups through multivariate modulation (MTVM). The co-incorporation of these groups in relation to the induced defects and their resultant structural, physical and electronic properties are investigated.

The modulators were introduced in a 1 to 1 ratio compared to the linker of the Zr-terephthalate (Zr-BDC) MOF UiO-66 (See ESI S.2 for conditions). All the samples were highly crystalline, as identified by powder X-ray diffraction (PXRD) (**Fig. 1b**). Pawley refinements confirmed phase purity (See ESI S.3.1) and showed that all pristine UiO-66 and MTVM UiO-66 materials refine in the *Fm-3m* space group, although a contraction of the unit cell is observed for the MTVM materials. Two small broad diffraction peaks that are not present in the pristine MOF (at *ca.* 4.3 and 5.5 2θ degrees), appear for the MTVM MOFs (**Fig. 1b** and Figs. S1-6), indicating the formation of nanodomains of defective *reo* phase.<sup>11</sup>

The incorporation of modulators, as characterised by acid-digested <sup>1</sup>H NMR (See ESI S.3.2 for detailed analysis, Figs S7-11), agreed with the modulator acidity – pK<sub>a</sub> SH (4.05) > NO<sub>2</sub>(3.44) > SO<sub>3</sub>(3.75 / <1) – for single-modulated MOFs,<sup>6</sup> with ratios of *ca.* 0.2, 0.07 and 0.04 modulators per linker for UiO-66-SO<sub>3</sub>, UiO-66-NO<sub>2</sub> and UiO-66-SH respectively (**Table 1**), which corresponds to 16.7, 6.7 and 3.9 mol%. The ratio of SO<sub>3</sub>/BDC agrees with previous work using this modulator as a hemilabile linker due to the ability of the sulfonate to coordinate with Zr<sub>6</sub> clusters.<sup>12</sup>



**Fig. 1:** a) Schematic representation of MTVM MOF with defect-induced *reo* topology in comparison with the pristine MOF. b) PXRD profiles c) amplification of FT-IR profiles highlighting  $\mu_3$ -O,  $\mu_3$ -OH and Zr-(OC) bands.

<sup>a</sup> Institut de Ciència Molecular, Universitat de València, Calle catedrático José Beltrán Martínez, 46980, Paterna, Valencia, Spain.

<sup>b</sup> Biomaterials and Bioengineering Lab, Translational Research Centre San Alberto Magno, Universidad Católica de Valencia San Vicente Mártir (UCV), Spain.

<sup>c</sup> Department of Materials Science and Metallurgy, 27 Charles Babbage road, University of Cambridge, CB30FS, Cambridge, United Kingdom.

Electronic Supplementary Information (ESI) available: [details of synthesis, characterisation, and properties of materials]. See DOI: 10.1039/x0xx00000x



**Table 1:** Characterisation data of the MOFs. Molar ratios compared to the linker ( $^1\text{H NMR}$ ), molar missing linker percent (TGA+  $^1\text{H NMR}$ ), Z-potential,  $S_{\text{BET}}$  surface area and total pore volume measured at  $P/P_0$  0.9 and estimated optical band gap (eV).

Sample	R NO <sub>2</sub> /BDC	R SO <sub>3</sub> /BDC	R SH/BDC	ML%	Z-potential	$S_{\text{BET}}$	Pore volume	Band gap
UiO-66	n/a	n/a	n/a	11.0	19.2	1315	0.516	4.21
UiO-66-NO <sub>2</sub>	0.072	n/a	n/a	15.2	49.1	1449	0.587	4.07
UiO-66-SO <sub>3</sub>	n/a	0.2	n/a	24.9	-5.9	1296	0.546	4.03
UiO-66-SH	n/a	n/a	0.041	9.5	32.2	1339	0.539	3.92
UiO-66-NO <sub>2</sub> /SO <sub>3</sub>	n/a	0.169	n/a	22.5	14.0	1359	0.548	3.92
UiO-66-NO <sub>2</sub> /SH	0.153	n/a	0.186	24.8	31.6	1409	0.563	3.62
UiO-66-SO <sub>3</sub> /SH	n/a	0.054	0.015	10.8	22.2	1266	0.52	3.80
UiO-66-NO <sub>2</sub> /SO <sub>3</sub> /SH	0.169	0.054	0.115	24.5	26.0	1348	0.54	3.67

In the di-modulated MOFs, different trends in incorporation are observed. For UiO-66-NO<sub>2</sub>/SO<sub>3</sub> the presence of Benz-NO<sub>2</sub> in the profiles is almost negligible, whereas Benz-SO<sub>3</sub> is slightly less incorporated than for the single modulated MOF. In UiO-66-NO<sub>2</sub>/SH, the Benz-SH modulator (less acidic) is surprisingly more incorporated than the NO<sub>2</sub>-derivative modulator, while in UiO-66-SO<sub>3</sub>/SH the most acidic modulator, Benz-SO<sub>3</sub>, is the most incorporated. Unexpectedly, Benz-SO<sub>3</sub> is the less incorporated in the tri-modulated sample, followed by Benz-SH and Benz-NO<sub>2</sub> derivatives. Interestingly, the unit cell contraction determined by Pawley refinements increases with the modulators incorporated.

The results of the specific synthetic set fully characterized enclosed in this manuscript are given in **Table 1**, but these trends have been reproduced and expressed as the average and standard deviation in ESI Section 3.2. The fact that the incorporation trends are not aligned with the modulator's acidity for MTVM MOFs, suggests that repulsion-attraction interactions can have a major role in dictating preferred incorporation.<sup>4</sup> This scenario highlights the complexity, jet beauty of coordination modulation and the need for comprehensive studies with large sets of samples to fully understand it.

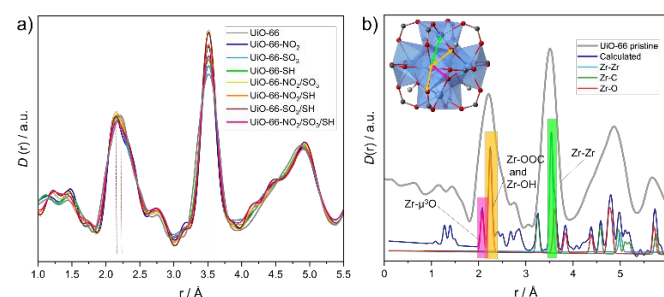
FTI-IR confirmed the incorporation through coordination, as while vibration bands from the modulators were present, the ones of free carboxylate groups were not observed (See ESI S3.3, Figs. S13-30). In agreement with previous work on Benz-SO<sub>3</sub> modulation, UiO-66-SO<sub>3</sub> displayed shifted bands from Benz-SO<sub>3</sub> coordination.<sup>12</sup> The vibration band that corresponds to  $\mu_3$ -O stretching (ca. 680 cm<sup>-1</sup>)<sup>13</sup> is shifted to ca. 660 cm<sup>-1</sup> upon modulation, with slight variations between samples (**Fig. 1c**). The band attributed to Zr-(OC) asymmetric stretching<sup>13</sup> has also a minor shift for the samples containing SO<sub>3</sub> groups. This information points out the deformation of the clusters by introducing modulating benzoic acid derivate species.

Thermo Gravimetry Analysis (TGA) revealed high thermal stability (ca. 500°C) upon defect introduction of modulators. A significant decrease in thermal stability (ca. 400°C) was observed only for the NO<sub>2</sub>-containing samples, being more noticeable for the single modulated. The composition of the frameworks was estimated by combining TGA and  $^1\text{H NMR}$  into mathematical equations (See ESI S3.4 for detailed assessment, Figs S31-36).<sup>14</sup> All the samples but UiO-66-SH displayed similar or higher defectivity than the pristine MOF, ranging from 10 to 25 molar % missing linkers (**Table 1**), with a minimum of 4.5 linkers out of 6 per Zr<sub>6</sub> clusters (9-connected instead of 12-connected units). In the single modulated frameworks, both the number of missing linkers and the incorporation of the

modulator agree to its  $pK_a$ . Within all the samples, a general but not-so-linear trend of increasing missing linkers (decreasing the linker-to-metal ratio) with the increased incorporation of modulators is observed (**Fig. S37**). UiO-66-SH is the only sample with a slightly lower missing linker percent than pristine UiO-66 (9% vs 11%). This modulator has a  $pK_a$  that stands between the  $pK_{a1}$  and  $pK_{a2}$  of BDC, and a similar log P. In fact, for this sample, the modulator (Benz-SH) and defect-compensating species (formic acid and acetic acid) are in a ratio of 2 compared to the missing linker, fully compensating for the missing linker vacancies, agreeing with recent findings on optimal modulators to boost UiO-66 crystallinity.<sup>15</sup>

X-ray total scattering experiments were conducted to analyze the local structure of UiO-66 and its defected MTVM-UiO-66 (See ESI S3.5, Figs S39-51).<sup>16</sup> The pair distribution function (PDF), denoted as  $D(r)$ , was used to maximise long-range correlations.<sup>17</sup> Pristine UiO-66  $D(r)$  showed expected correlations similar to the reported UiO-66 *fcu* model (**FigS. S40-43**), including Zr-O (2.2 Å), Zr...Zr (3.5 Å) sharing edges and vertexes and Zr...Zr (4.86 Å) sharing edges within the same cluster. Zr...Zr distances between clusters were also observed in the pristine UiO-66 (**Fig. S42**). MTVM-UiO-66  $D(r)$ s exhibited equivalent correlations compared to the pristine MOF, but long-range order peaks had a smaller area due to increased disorder and defects.

More in detail, Zr-O peak centred at 2.2 Å for the pristine UiO-66 is slightly shifted to the left, and a shoulder is also distinguished for the defective samples, as represented in **Fig. 2a**, suggesting the presence of two different contributions. In addition, Zr-Zr correlations (3.5 Å) of MTVM-UiO-66 derivatives show larger areas, which might indicate a higher number of coordinated Zr, considering the presence of *reo* phase according to PXRD patterns. To our knowledge, these facts in PDF patterns have never been reported in Zr-UiO-66 derivatives.



**Fig. 2:** a) PDF of the MOFs in the 1.0-5.5 Å range showing peaks centred at 2.2 and 3.5 Å typical from Zr-O and Zr...Zr correlations, respectively. b) Comparison of the experimental  $D(r)$  of the pristine UiO-66 with the calculated partial  $g(r)$ s using PDFGUI (ADP values are approached to 0.0005). Main correlations are highlighted in pink, yellow and green.

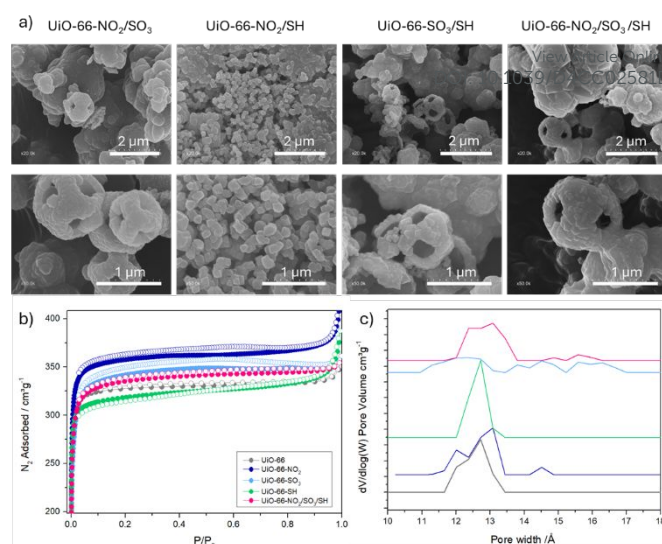


Motivated by the lack of information, total and partial PDFs were recalculated using PDFGUI minimising the ADP values to 0.0005 (Fig. 2.b and S44-45), to extract the contributions from different atom distances.<sup>18</sup> C-H and O-H Contributions are omitted because of their low contribution to the total PDF (Figs. S44-45). Peaks centred at 2.07 Å and 2.24 Å correspond to Zr-O- $\mu_3$  and Zr-O<sub>COO</sub> and Zr-O<sub>OH</sub>, respectively. Gaussian deconvolution of the pristine UiO-66 peaks centred at 2.2 and 2.78 Å shows a total of 4 peaks (Figs. S46-47 and Table S10). Peak 1 (2.01 Å), and peak 2 (2.21 Å) correspond to the Zr-O- $\mu_3$ , Zr-O<sub>COO</sub> and Zr-O<sub>OH</sub>, respectively for the pristine sample, whilst peaks 3 and 4 are combined contributions from C-C, C-O and O-O correlations. However, in MTVM-UiO-66 materials, peaks 1-4 appear to shift to the left, suggesting a change in the proportion of the partial correlations or the presence of a different dimensionality of Zr-nodes at the local scale.<sup>19-21</sup> This hypothesis also agrees with an increment of the integrated area of the peak located at 3.5 Å (Table S11, Fig. S48) and shifted peaks located at 4.3, 4.5 and 4.9 Å (Figs. S49-50). PDF patterns for various Zr-node configurations were computed to compare the 2.2 Å peak, indicating shorter correlations with higher atom counts per node (Fig. S51). However, further analysis must be carried out to obtain a potential model.

The particle size and morphology were analysed by scanning electron microscopy (SEM) (Fig. 3a, See ESI S.3.6, Figs. S52-55). The pristine sample is composed of monodisperse octahedral particles of 296 ± 10 nm. All the samples that do not contain the Benz-SO<sub>3</sub> modulator have also octahedral morphology, and a decrease in particle size, suggesting a capping effect, although the modulator/linker ratio rules out solely incorporation at the particles' surface.<sup>22</sup> Upon the addition of the Benz-SO<sub>3</sub> modulator, the samples are composed of intergrown particles and hollow superstructures of ca. 1-3 μm, formed out of nanoparticles of ca 50-100 nm. The reason why these superstructures are formed escapes the understanding of this communication and shall require further study, but we postulate that surface-bond sulfonate groups could be involved. Energy Dispersed X-Ray Analysis (EDX) (Fig. S56) mapping confirmed the homogeneous distribution of S-containing modulators within the structure. The presence of K or Na ions compensating for the charge of unbound SO<sub>3</sub> modulators was discarded by EDX, which showed S/Zr ratios higher than expected for the estimated structure, pointing out the modulators' partial surface incorporation, although this could be affected by interference leading to overestimated S determination and shall be interpreted with caution (Fig. S57).

Surface charge is related to defectivity among other factors.<sup>23</sup> All the samples display positive Z-potentials (Table 1), apart from UiO-66-SO<sub>3</sub>, whose negative Z-potential suggests the presence of partial tangling sulfonate groups. The rest of the samples (apart from UiO-66-NO<sub>2</sub>/SO<sub>3</sub>) have an increase in Z-potential, which is not solely related to their defective nature (See ESI S3.7, Figs. S58-68).

N<sub>2</sub> adsorption and desorption isotherms were recorded to evaluate the effect of defect multifunctionalisation on the materials (See ESI S.8, Figs. S78-81). All the samples displayed higher porosity than expected for pristine UiO-66 (ca. 1220 m<sup>2</sup>g<sup>-1</sup> SBET and 0.40 cm<sup>3</sup>g<sup>-1</sup> pore volume).<sup>6</sup> Our pristine sample, with ca 10 molar% of missing



**Fig. 3:** a) SEM images, b) N<sub>2</sub> adoption/desorption isotherms of pristine, single-modulated and tri-modulated UiO-66 and c) pore size distribution calculated with NLDFT pillared clay cylindrical pore model.

linkers has a surface area of ca. 1315 m<sup>2</sup>g<sup>-1</sup> (Table 1). Despite introducing significant functionality, the lowest surface area was ca. 1266 m<sup>2</sup>g<sup>-1</sup> for UiO-66-SO<sub>3</sub>/SH, which displayed a similar linker-to-metal ratio to the pristine sample. A general increase in porosity was observed up to S<sub>BET</sub> 1449 m<sup>2</sup>g<sup>-1</sup> for UiO-66-NO<sub>2</sub>, whereas UiO-66-NO<sub>2</sub>/SO<sub>3</sub>/SH exhibited an S<sub>BET</sub> of ca. 1348 m<sup>2</sup>g<sup>-1</sup> despite containing ca 15 w/w% of functionalized modulators. The pore size distribution revealed significant differences in the microporous character of the samples. In agreement with the similar defectivity of UiO-66-SH and the pristine sample, their pore size distribution is similar. The rest of the samples have pore features of the nano-ordered *reO* phase.<sup>24</sup>

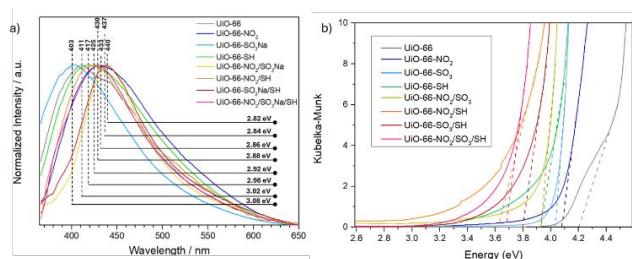
Since the modulators introduced to UiO-66 shall alter its electronic structure,<sup>25</sup> we applied Photoluminescence (PL) measurements to provide information about the electronic transitions, which are also related to their defective nature (See ESI S3.9, Figs. S82-91).<sup>23</sup> MOFs with fewer defects, enhanced charge transfer, and more ligands will exhibit greater PL emission.<sup>26</sup> While the SH group is an electron donor group, the SO<sub>3</sub> and NO<sub>2</sub> groups are electron withdrawers; thus, the charge transfer between the clusters and the ligands will be different. It is important to remark that the analysis of PL in MOFs is complex due to the sensitivity of emission spectra to different factors, such as charge transfer, size, presence of defects and crystallinity among others.

A reduction in the emission intensity is observed with the addition of the -SH modulator (Figure S82). A more pronounced behavior occurs with the -NO<sub>2</sub> modulator, due to the greater decrease in the linker/metal ratio. In the case of the SO<sub>3</sub> modulator, only a slight reduction in intensity compared to the pristine sample is observed, as it is not only altering the electron density but also acting as a new linker.

This behaviour leads to a higher efficiency of charge transfer between the metal centres and the hemilabile Benz-SO<sub>3</sub> linker, consequently increasing PL emission compared to the other modulators. For samples with multiple modulators, a balance between the defects caused by the -SH and -NO<sub>2</sub> modulators and the improvement in charge transfer by -SO<sub>3</sub> is observed.







**Fig. 4:** a) Normalised photoluminescence spectra of the MOFs. b) Kubelka-Munk and tau plot of the samples to extract the bandgap.

The maximum emission wavelength can also provide information about the degree of defects, as it is affected by the energy gap between the excited ligand and the metal cluster.<sup>27</sup> In **Fig. 4a**, it can be observed that the  $-\text{SO}_3$  modulator causes a blue shift in the maximum PL emission, indicating more energetic contributions in the forbidden region of the band gap compared to the pristine sample, due to its role as a new linker, while the  $-\text{NO}_2$  and  $-\text{SH}$  modulators cause red shifts, indicating the creation of new, less energetic energy levels within the forbidden region of the band gap. The emission of samples with multiple modulators all undergoes a redshift, indicating that the defects generated by the  $-\text{NO}_2$  and  $-\text{SH}$  modulators outweigh the improvement in charge transfer caused by  $-\text{SO}_3$ . These results are supported through emission spectra deconvolutions presented in Section S.3.9 (Figs. S83-91). Diffuse reflectance was applied to study the optoelectronic properties of the materials and to estimate their band gap (See S3.10 Figs. S92-96 and **Table 1**). All MOFs showed a decrease in band gap compared to pristine UiO-66 (4.21 eV), as represented in **Fig. 4b**. Among the single-modulated MOFs, a smaller band gap was found for UiO-66-SH, whereas all the SH-containing multi-modulated samples have a more significant bandgap decrease, which might be affected by the higher defect induction. This result aligns with the PL findings, as adding modulators or their combination can create structural defects, altering electronic transfer processes.

All in all, the MTVM approach is proven as a versatile method for the *in-situ* defect multifunctionalisation of MOFs, increasing their porosity. Introducing functional modulators alters the  $\text{Zr}_6$  clusters of the MOF, as evidenced by FT-IR and PDF, and tunes their electronic transitions and optoelectronic properties, decreasing the band gap. We anticipate that this methodology may impact the catalytic properties of MOFs among other applications.

IAL conceptualized, supervised the project, and acquired funding. CRM synthesized and characterized the materials. IAL, CRM, CCB and MA collected the PDF data. CCB treated, analysed and interpreted the PDF data. MA collected and interpreted the PL data. IAL and CRM wrote the first draft of the manuscript with input from all authors. The project that gave rise to these results received the support of a fellowship from “la Caixa” Foundation (LCF/BQ/PR23/11980041). PDF experiments were performed at BL-04 MSPD at ALBA Synchrotron (2023087671) with the collaboration of ALBA staff. MA thanks the “Juan de la Cierva” fellowship (JDC2022-049934-I). CCB thanks Leverhulme Trust Research Project Grant (RPG-2020-005).

## Data availability

Data for this article, including full characterisation, are available at Zenodo at [10.5281/zenodo.12625580].

## Conflicts of interest

There are no conflicts to declare.

View Article Online  
DOI: 10.1039/D4CC02581D

## Notes and references

- R. S. Forgan, *Chem. Sci.*, 2020, **11**, 4546–4562.
- F. Bigdeli, M. N. A. Fetzer, B. Nis, A. Morsali and C. Janiak, *J. Mater. Chem. A*, 2023, **11**, 22105–22131.
- I. A. Lázaro, H. Szalad, P. Valiente, J. Albero, H. García and C. Martí-Gastaldo, *ACS Appl. Mater. Interfaces*, 2022, **14**, 21007–21017.
- I. Abánades Lázaro, *J. Mater. Chem. A*, 2022, **10**, 10466–10473.
- M. Taddei, *Coord. Chem. Rev.*, 2017, **343**, 1–24.
- G. C. Shearer, S. Chavan, S. Bordiga, S. Svelle, U. Olsbye and K. P. Lillerud, *Chem. Mater.*, 2016, **28**, 3749–3761.
- W. Jiang, C. Liang and Y. Zhang, *Adv. Funct. Mater.*, 2024, 2308946–2308969.
- H. Furukawa, U. Müller and O. M. Yaghi, *Angew. Chem. Int. Ed.*, 2015, **54**, 3417–3430.
- H. Deng, C. J. Doonan, H. Furukawa, R. B. Ferreira, J. Towne, C. B. Knobler, B. Wang and O. M. Yaghi, *Science*, 2010, **327**, 846–850.
- I. Abánades Lázaro, C. J. R. Wells and R. S. Forgan, *Angew. Chem. Int. Ed.*, 2020, **59**, 5211–5217.
- 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, *Nat. Commun.*, 2014, **5**, 4176.
- X. Feng, J. Hajek, H. S. Jena, G. Wang, S. K. P. Veerapandian, R. Morent, N. D. Geyter, K. Leyssens, A. E. J. Hoffman, V. Meynen, C. Marquez, D. E. D. Vos, V. V. Speybroeck, K. Leus and P. V. D. Voort, *J. Am. Chem. Soc.*, 2020, **142**, 3174–3183.
- L. Valenzano, B. Civalieri, S. Chavan, S. Bordiga, M. H. Nilsen, S. Jakobsen, K. P. Lillerud and C. Lamberti, *Chem. Mater.*, 2011, **23**, 1700–1718.
- I. Abánades Lázaro, *Eur. J. Inorg. Chem.*, 2020, **2020**, 4284–4294.
- F. E. Chen, T. A. Pitt, D. J. Okong’o, L. G. Wetherbee, J. J. Fuentes-Rivera and P. J. Milner, *Chem. Mater.*, 2022, **34**, 3383–3394.
- C. Castillo-Blas, J. M. Moreno, I. Romero-Muñiz and A. E. Platero-Prats, *Nanoscale*, 2020, **12**, 15577–15587.
- D. A. Keen, *J. Appl. Crystallogr.*, 2001, **34**, 172–177.
- C. L. Farrow, P. Juhas, J. W. Liu, D. Bryndin, E. S. Božin, J. Bloch, T. Proffen and S. J. L. Billinge, *J. Phys.: Condens. Matter*, 2007, **19**, 335219–335227.
- H. Jiang, W. Zhang, X. Kang, Z. Cao, X. Chen, Y. Liu and Y. Cui, *J. Am. Chem. Soc.*, 2020, **142**, 9642–9652.
- S. Leubner, H. Zhao, N. V. Velthoven, M. Henrion, H. Reinsch, D. E. D. Vos, U. Kolb and N. Stock, *Angew. Chem. Int. Ed.*, 2019, **131**, 11111–11116.
- F. C. N. Firth, M. W. Gaultois, Y. Wu, J. M. Stratford, D. S. Keeble, C. P. Grey and M. J. Cliffe, *J. Am. Chem. Soc.*, 2021, **143**, 19668–19683.
- G. Oberdörster, E. Oberdörster and J. Oberdörster, *Environ. Heal. Perspect.*, 2005, **113**, 823–839.
- W. Morris, S. Wang, D. Cho, E. Auyeung, P. Li, O. K. Farha and C. A. Mirkin, *ACS Appl. Mater. Interfaces.*, 2017, **9**, 33413–33418.
- W. Liang, C. J. Coghlan, F. Ragon, M. Rubio-Martinez, D. M. D’Alessandro and R. Babarao, *Dalton Trans.*, 2016, **45**, 4496–4500.
- A. D. Vos, K. Hendrickx, P. V. D. Voort, V. V. Speybroeck and K. Lejaeghere, *Chem. Mater.*, 2017, **29**, 3006–3019.
- Y. Fu, J. Wu, R. Du, K. Guo, R. Ma, F. Zhang, W. Zhu and M. Fan, *RSC Adv.*, 2019, **9**, 37733–37738.
- H. Zhu, J. Huang, Q. Zhou, Z. Lv, C. Li and G. Hu, *J. Lumin.*, 2019, **208**, 67–74.

