



Cite this: *Chem. Commun.*, 2024, 60, 8280

Received 28th May 2024,
Accepted 5th July 2024

DOI: 10.1039/d4cc02581d

rsc.li/chemcomm

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

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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 –NO₂, –SO₃ 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.^{1,2} 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.^{3,4} Defect engineering has received significant attention as defects can tune the physical and electronic properties of materials.^{5,6} In the same context, increasing the heterogeneity of MOFs through functionalization is also a hot topic with enhancement in diverse applications.^{7,8} 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.⁹ 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.^{4,10} 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 –SO₃[–], –NO₂ and –SH 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). All the samples were highly crystalline, as identified by powder X-ray diffraction (PXRD) (Fig. 1b). Pawley refinements confirmed phase purity (see ESI† S3.1) and showed that all pristine UiO-66 and MTVM UiO-66 materials refine in the *Fm* $\bar{3}$ *m* 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 Fig. S1–S6, ESI†), indicating the formation of nanodomains of defective *reo* phase.¹¹

The incorporation of modulators, as characterised by acid-digested ¹H NMR (Fig. S7–S11, ESI†), agreed with the modulator acidity – p*K*_a SH (4.05) > NO₂ (3.44) > SO₃ (3.75/<1) -for

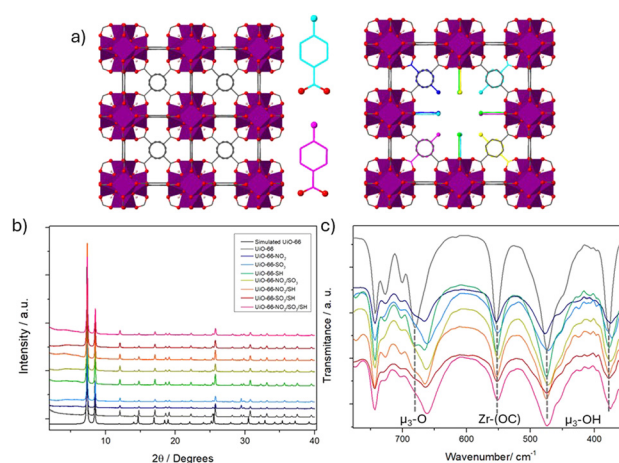


Fig. 1 (a) Schematic representation of MTVM MOF with defect-induced *reo* topology compared with the pristine MOF. (b) PXRD profiles (c) FT-IR profiles highlighting μ₃-O, μ₃-OH and Zr-(OC) bands.

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† Electronic supplementary information (ESI) available: Details of synthesis, characterisation, and properties of materials. See DOI: <https://doi.org/10.1039/d4cc02581d>



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.⁴ This scenario highlights the complexity, yet beauty of coordination modulation and the need for comprehensive studies with large sets of samples to fully understand it.

Thermo Gravimetry Analysis (TGA) revealed high thermal stability (*ca.* 500 °C) upon defect introduction of modulators, with only a significant decrease (to *ca.* 400 °C) for the NO₂-containing samples. The composition of the frameworks was

X-ray total scattering experiments were conducted to analyze the local structure of the MOFs (Fig. S39–S51, ESI†).¹⁶ The pair distribution function (PDF), denoted as $D(r)$, was used to maximise long-range correlations.¹⁷ Pristine UiO-66 $D(r)$ showed expected correlations similar to the reported UiO-66 *fcu* model (Fig. S40–S43, ESI†), 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, ESI†). 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.

Motivated by the lack of information, total and partial PDFs were recalculated using PDFGUI minimising the ADP values to 0.0005 (Fig. 2b and Fig. S44–S45, ESI[†]), to extract the contributions from different atom distances.¹⁸ C–H and O–H Contributions are omitted because of their low contribution to the total

Sample	R NO ₂ /BDC	R SO ₃ /BDC	R SH/BDC	ML%	Z-potential	S _{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 ₂	0.072	n/a	n/a	15.2	49.1	1449	0.587	4.07
UiO-66-SO ₃	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 ₂ /SO ₃	n/a	0.169	n/a	22.5	14.0	1359	0.548	3.92
UiO-66-NO ₂ /SH	0.153	n/a	0.186	24.8	31.6	1409	0.563	3.62
UiO-66-SO ₃ /SH	n/a	0.054	0.015	10.8	22.2	1266	0.52	3.80
UiO-66-NO ₂ /SO ₃ /SH	0.169	0.054	0.115	24.5	26.0	1348	0.54	3.67



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.

PDF (Fig. S44–S45, ESI†). Peaks centred at 2.07 Å and 2.24 Å correspond to Zr–O–μ₃ and Zr–O_{COO} and Zr–O_{OH}, respectively. Gaussian deconvolution of the pristine UiO-66 peaks centred at 2.2 and 2.78 Å shows a total of 4 peaks (Fig. S46–S47 and Table S10, ESI†). Peak 1 (2.01 Å), and peak 2 (2.21 Å) correspond to the Zr–O–μ₃, Zr–O_{COO} and Zr–O_{OH}, 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 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.^{19–21} This hypothesis also agrees with an increment of the integrated area of the peak located at 3.5 Å (Table S11 and Fig. S48, ESI†) and shifted peaks located at 4.3, 4.5 and 4.9 Å (Fig. S49–S50, ESI†). 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, ESI†). 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. S53 and Fig. S52–S55, ESI†). The pristine sample is composed of monodisperse octahedral particles of 296 ± 10 nm. All the samples that do not contain the Benz-SO₃ 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.²² Upon the addition of the Benz-SO₃ 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, ESI†) 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 SO₃ 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, ESI†).

Surface charge is related to defectivity among other factors.²³ All the samples display positive Z-potentials (Table 1), apart from UiO-66-SO₃, whose negative Z-potential suggests the presence of partial tangling sulfonate groups. The rest of the samples (apart from UiO-66-NO₂/SO₃) have an increase in Z-potential, which is not solely related to their defective nature (Fig. S58–S68, ESI†).

N₂ adsorption and desorption isotherms were recorded to evaluate the effect of defect multifunctionalisation on the materials (Fig. S78–S81, ESI†). All the samples displayed higher porosity than expected for pristine UiO-66 (*ca.* 1220 m² g^{−1} S_{BET} and 0.40 cm³ g^{−1} pore volume).⁶ Despite introducing significant functionality, the lowest surface area was *ca.* 1266 m² g^{−1} for UiO-66-SO₃/SH, which displayed a similar linker-to-metal ratio to the pristine sample. A general increase in porosity was observed up to S_{BET} 1449 m² g^{−1} for UiO-66-NO₂, whereas UiO-66-NO₂/SO₃/SH exhibited an S_{BET} of *ca.* 1348 m² g^{−1} 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.²⁴

Since the modulators introduced to UiO-66 shall alter its electronic structure,²⁵ we applied Photoluminescence (PL) measurements to provide information about the electronic transitions, which are also related to their defective nature (Fig. S82–S91, ESI†).²³ MOFs with fewer defects, enhanced charge transfer, and more ligands will exhibit greater PL emission.²⁶ While the SH group is an electron donor group, the SO₃ and NO₂ 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 (Fig. S82, ESI†). A more pronounced behavior occurs with the –NO₂ modulator, due to the greater decrease in the linker/metal ratio. In the case of the SO₃ 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-SO₃ 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 –NO₂ modulators and the improvement in charge transfer by –SO₃ is observed.

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.²⁷ In Fig. 3a, it can be observed that the –SO₃ 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 –NO₂ and –SH modulators cause red shifts, indicating the creation of new, less energetic energy levels



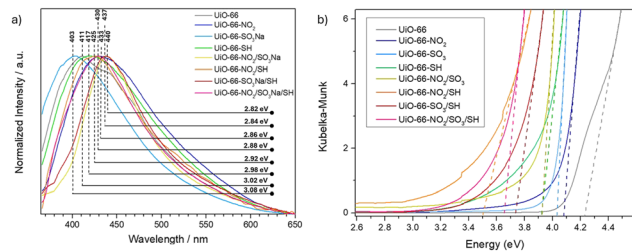


Fig. 3 (a) Normalised photoluminescence spectra of the MOFs. (b) Kubelka–Munk and tau plot of the samples to extract the bandgap.

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 (Fig. S83–S91, ESI†). Diffuse reflectance was applied to study the optoelectronic properties of the materials and to estimate their band gap (Fig. S92–S96, ESI† and Table 1). All MOFs showed a decrease in band gap compared to pristine UiO-66 (4.21 eV), as represented in Fig. 3b. 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 Zr_6 clusters of the MOF, and tunes their electronic transitions and optoelectronic properties. 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 CMR 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 <https://doi.org/10.5281/zenodo.12625580>.

Conflicts of interest

There are no conflicts to declare.

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