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Multivariate modulation of Zr_6 UiO-66 for enhanced cooperative CO_2 adsorption through defect multi-functionalisation

A powerful strategy to enhance CO_2 capture by combining pore defect engineering with chemical heterogeneity in a single synthetic step. The approach offers a versatile platform for tuning host-guest interactions, which could be applied across a broad range of applications, from gas separation to catalysis and drug delivery.

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Multivariate modulation of Zr₆ UiO-66 for enhanced cooperative CO₂ adsorption through defect multi-functionalisation†

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The multivariate modulation of MOFs allows for the simultaneous introduction of multiple functionalities at defect sites during synthesis, enhancing the MOF porosity. By the thoughtful choice of modulators' functionalities targeted at CO₂ adsorption, the designed dimodulated MOF, UiO-66-NH₂/SO₃, has a 6.6 mmol g⁻¹ CO₂ adsorption at 273 K and 1 bar, a 2.3-fold increase compared to the pristine MOF and a 1.6-fold enhancement compared to the single-modulated MOFs. This enhancement is due to the cooperative effect of functional units, which is supported by Monte Carlo simulations.

Introduction

Carbon capture technologies have attracted significant attention to remove CO₂ from the atmosphere and mitigate global warming.¹ In this regard, metal-organic frameworks (MOFs) are promising materials due to their high surface areas, excellent thermal and chemical stabilities and tuneable structure.²⁻⁵

Until now, different strategies have been applied to enhance the CO₂ adsorption capacity and selectivity of MOFs.⁶ These include functionalisation,^{7,8} metal doping,⁹ confinement of solvents such as ionic liquids¹⁰ and defect engineering.^{11,12}

Introducing multiple functional groups that selectively interact with the carbon and oxygen atoms of CO₂ could significantly improve adsorption properties. However, examples of such a

New concepts

This manuscript explores the pore engineering of metal-organic frameworks (MOFs) through multivariate modulation in the context of cooperative CO₂ adsorption. This strategy enables the simultaneous incorporation of multiple functional groups as defect-inducing modulators during synthesis. By selecting functionalities with complementary interactions, the CO₂ adsorption capacity is enhanced by 2.3-fold, as supported by Monte Carlo simulations. While multi-functionalisation and defect engineering have independently improved the adsorption capacity and selectivity of MOFs, this is the first time both are combined specifically for CO₂ capture. This method not only enables cooperative CO₂ binding through diverse functional units, but also increases the materials' porosity *via* controlled defect formation, addressing one of the key limitations of multivariate MOFs based on multiple linkers. We believe that this methodology will impact the many applications of MOFs, as combining defect engineering with heterogeneity can be used to tune the host-guest interactions through pore environment control. Beyond CO₂ adsorption, this approach could be applied to favour the uptake of other gases for storage and separation, as well as the removal of contaminants for water remediation. It will also enable the introduction of cooperative units for catalysis or even drugs and targeting units for targeted drug delivery, among other possibilities.

cooperative approach remain limited compared with single-functionalisation.¹³⁻¹⁶ Moreover, the combination of defect engineering with multi-functionalisation has yet to be explored in the context of CO₂ adsorption, providing not only multiple functional units for cooperative adsorption, but also an increase in porosity due to the generated defects. We have recently introduced the concept of multivariate modulation of MOFs (MTVM MOFs),¹⁷⁻¹⁹ in which multiple functional units are incorporated during synthesis using modulators as aliovalent defect-compensating ligands, enhancing the MOF's porosity and tailoring their properties. We anticipate that MTVM of MOFs will have broad applications as a pore engineering method to enhance CO₂ adsorption, enabling fine-tuning of host-guest interactions within the pore environment through defect multi-functionalisation, given the binding geometries of modulators.

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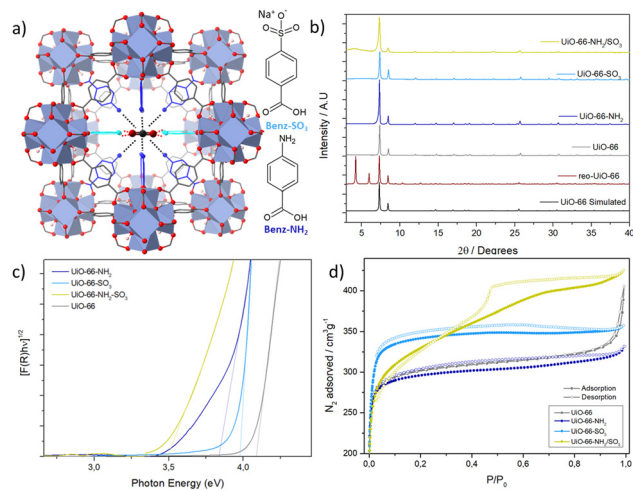


Fig. 1 (a) Schematic representation of MTVM **reo** UiO-66 with pore engineering targeted at enhanced CO₂ adsorption. (b) PXRD profiles. (c) Tauc plots and (d) N₂ adsorption and desorption isotherms at 77 K.

Herein, we present the proof-of-concept application of MTVM MOFs to increase CO₂ adsorption capacity by introducing two functional units simultaneously to enhance CO₂ adsorption of the Zr₆-terephthalate UiO-66 *via* aliovalent substitution (Fig. 1a). We have chosen amino and sulfonic acid *p*-functionalised benzoic acid modulators targeting complementary interactions with CO₂.^{7,8} The -NH₂ group is mainly known to interact with the acidic carbon of CO₂ through dipole-quadrupole interactions involving its nitrogen. On the other hand, the -SO₃Na group, besides S and O lone pair interaction introduces strong electrostatic interactions and also exhibits flexibility in the directionality of the S-O⁻ bond and C-S bond rotation, which maximizes intermolecular interactions.²⁰ This combination results in a *ca.* 2.3-fold increase compared to the pristine defective MOF and a 1.6-fold increase compared with the single-functionalised MOFs, presenting a 6.6 mmol g⁻¹ adsorption at 273 K and 1 bar.

Results and discussion

Materials synthesis and characterisation

The modulators were introduced in a 1 : 1 ratio compared to the linker of the Zr-terephthalate MOF UiO-66 (see S.2, ESI[†]). Powder X-ray diffraction (PXRD) (Fig. 1b, S.3.1 for full PXRD patterns, ESI[†]) revealed crystalline **fcu** frameworks with broad diffraction bands characteristic of the formation of missing cluster **reo** nanodomains in the SO₃-modulated and dimodulated MOFs.²¹ The Benz-NH₂ modulator was incorporated

by *ca.* 5 mol% compared to the linker in UiO-66-NH₂ and Benz-SO₃ by *ca.* 16.7 mol% in UiO-66-SO₃, as characterised by acid-digested ¹H NMR (see S.3.2, ESI[†], Table 1). This difference is attributed to the distinct pK_a of the modulators, being Benz-SO₃ the most acidic. The incorporation of modulators increased in UiO-66-NH₂/SO₃, displaying a *ca.* 12 mol% of Benz-NH₂ and *ca.* 24 mol% of Benz-SO₃, suggesting attractive interactions between the modulators.¹⁸

Fourier transform infrared spectroscopy (FT-IR) confirmed the modulator's attachments to the Zr₆ clusters, showing no free carboxylate bands from modulators despite their incorporation (see S.3.3, ESI[†]). Shifting of the Zr₆ bands was also observed in line with their coordination to the metal clusters. In agreement with our previous work, UiO-66-SO₃ displayed new bands attributed to asymmetric and symmetric stretching frequencies of sulfonate (see S.3.3, ESI[†]),¹⁹ which shifting indicates partial attachment of sulfonate groups to Zr clusters. Further shifting is observed upon the inclusion of Benz-NH₂ in UiO-66-NH₂/SO₃, suggesting possible interactions between the sulfonate and amino group from the modulators, explaining the increased incorporation compared to single-modulated samples.

Thermogravimetric analysis (TGA) confirmed the samples' thermal stability (up to *ca.* 500 °C), with the modulators decomposing at similar temperatures to the linker. The composition of the frameworks was estimated by combining TGA and ¹H NMR into mathematical equations (see S.3.4, ESI[†]).²² The pristine MOF had *ca.* 14.3 mol% of missing linkers. According to the pK_a and incorporation of the modulators into single-modulated MOFs, UiO-66-NH₂ exhibits a *ca.* 17.5 mol% of missing linkers whereas UiO-66-SO₃ a *ca.* 24.9 mol%. In line with the higher incorporation of modulators UiO-66-NH₂/SO₃ displayed a *ca.* 40 mol% of missing linkers.

Energy dispersed X-ray analysis (EDX) mapping (see S.3.5, ESI[†]) confirmed the homogeneous distribution of modulators within the MOFs. The pristine MOF is composed of octahedral monodisperse particles of *ca.* 255 ± 38 nm and the addition of Benz-NH₂ does not significantly alter particle size (*ca.* 256 ± 33 nm), as analysed by scanning electron microscopy (SEM) (see S.3.5, ESI[†]). UiO-66-SO₃ and UiO-66-NH₂/SO₃ form yolk-shell superstructures of *ca.* 1–3 μm from the assembly of octahedral nanoparticles of *ca.* 50–100 nm. We hypothesise this phenomenon to be due to the formation of micelles or aggregates of sulfonate modulators and Zr during synthesis,²³ forming the yolk from which Zr ions connect and form the MOF shell within the yolk-shell superstructure.²⁴

The surface charge, as determined by Z-potential in water, agrees with their surface functionality (Table 1). UiO-66-NH₂/SO₃ does not present two Z-potential contributions (negative

Table 1 Characterisation data of the MOFs. Molar ratios compared to the linker (¹H NMR), molar missing linker percent (TGA + ¹H NMR), Z-potential, S_{BET} surface area and total pore volume measured at P/P₀ 0.9. Indirect optical band gap

Sample	R NH ₂ /BDC	R SO ₃ /BDC	ML%	Z-potential (mV)	S _{BET} (m ² g ⁻¹)	Pore volume (cm ³ g ⁻¹)	Band gap (eV)
UiO-66	n/a	n/a	14.35	35.4	1191	0.52	4.08
UiO-66-NH ₂	0.061	n/a	17.57	47.1	1184	0.50	3.80
UiO-66-SO ₃	n/a	0.2	24.89	-29.7	1296	0.55	3.96
UiO-66-NH ₂ /SO ₃	0.133	0.317	40.36	38.9	1167	0.65	3.47



and positive) from two different functionalised samples, as did our control of mixed UiO-66-NH₂ and UiO-66-SO₃, but an overall positive Z-potential due to the framework and Benz-NH₂ contribution surpassing the negative charge provided by Benz-SO₃ (see S.3.6, ESI†). The MOFs were stable upon stirring in water, methanol, acetonitrile and chloroform for 24 hours, as envisioned by PXRD, SEM, FT-IR and ¹H NMR, with no significant modulators' detachment (see S3.7, ESI†).

Diffuse reflectance was used to estimate the optical bandgap of the materials (Fig. 1c and Table 1). Introducing the electron-donating Benz-NH₂ reduces the band gap of UiO-66 to a greater extent than the electron-withdrawing Benz-SO₃.^{25,26} Combining the two within one framework had a cooperative effect, further decreasing the band gap (see S.3.8, ESI†) due to the formation of new gap states.²⁶

N₂ adsorption and desorption isotherms were recorded at 77 K to evaluate the effect of the modulators on the MOFs' porosity (see S.3.9, ESI†). The pristine MOF had a surface area of 1191 m² g⁻¹, in agreement with the reported surface areas of UiO-66 (1200 m² g⁻¹).²⁷ The single-modulated MOFs display type I isotherms with similar surface areas (Fig. 1d and Table 1) despite having slightly higher molecular weights (determined by TGA) and the pore space that functional groups occupy. Interestingly, UiO-66-NH₂/SO₃, shows a type IV isotherm characteristic of mesoporous materials, which agrees with its high degree of defectivity. Consequently, the pore volume of this sample is increased to *ca.* 0.65 cm³ g⁻¹, a 1.3-fold increase compared to our pristine MOF.

The pore size distributions of the modulated MOFs showed the appearance of new pores at 13–17 Å due to small nanoregions of missing clusters,²⁸ while UiO-66-NH₂/SO₃ had additional mesopores of *ca.* 5 nm, indicating that the defective regions within this MOF are much larger. We have not encountered this phenomenon for other di- and tri-modulated UiO-66 MOFs,^{18,19} suggesting that the monocarboxylate ligands with amino and sulfonate groups contribute synergistically to the defect formation during synthesis.

In situ monitoring of self-assembly

To understand the self-assembly of these materials, we recorded the time evolution of their small-angle X-ray scattering (SAXS) during their synthesis for 3 hours with a time interval of 30 s (see S.4, ESI†).²⁹ Fig. 2 shows the SAXS evolution of UiO-66 and UiO-66-NH₂/SO₃. All the syntheses start forming an amorphous intermediate, which has a bigger particle size for the Benz-SO₃-syntheses, indicated by the intensity of the scattering at low *q*.

The MOFs crystallise at relatively similar times (after *ca.* 28–35 minutes of reaction time) in the following order UiO-66-NH₂-SO₃ > UiO-66-SO₃ > UiO-66-NH₂ > UiO-66 (see S.4, ESI†). It was expected that a more acidic modulator would slow the crystallisation kinetics due to the decrease in the reaction pH,³⁰ but the opposite was encountered, possibly due to the coordination of the sulfonate group to Zr clusters and the synergic effect of NH₂ and SO₃ modulators. All the MOFs start crystallising from the ⟨111⟩ reflection, which displays higher intensity

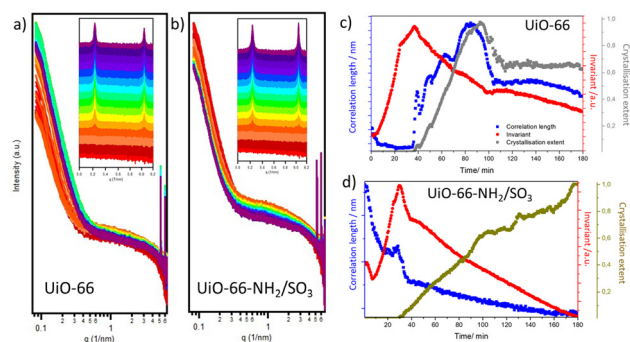


Fig. 2 Time evolution SAXS profiles of (a) UiO-66 and (b) UiO-66-NH₂/SO₃. Comparison of the crystallisation extent of the ⟨111⟩ reflection band with the invariant and correlation length profiles for (c) UiO-66 and (d) UiO-66-NH₂/SO₃.

than the ⟨200⟩ reflection over the course of the reaction for UiO-66 and UiO-66-NH₂, for which the two bands follow identical kinetics. In contrast, the intensity of the ⟨200⟩ band within UiO-66-SO₃ and UiO-66-NH₂/SO₃ gains significance during the reaction and becomes more intense than the ⟨111⟩ band, differing in their crystallisation kinetics. This highlights their different self-assembly mechanism and suggests selective modulator attachment.

The integrated parameters were computed to provide insights into nucleation and crystallisation (see S.4, ESI†). The correlation length gives information about the surface-to-volume ratio, which is related to particle size changes, while the invariant is related to the particle volume concentration.²⁹ The invariant is at its maximum when diffraction bands start to appear for all the MOFs and decrease during the growth phase, meaning that nucleation does not significantly persist during growth. For the UiO-66 and UiO-66-NH₂, the increase in correlation length together with the decrease of the invariant at the start of crystallisation indicates that the MOFs undergo coalescence,³¹ while further changes are aligned with fluctuations in the crystallisation extent. When a decrease in the Bragg reflections' intensity is encountered, a decrease in the correlation length and the invariant are observed, meaning a smaller concentration of smaller particles and indicating the precipitation of bigger particles, as observed in the capillary at the end of the reaction. Characterisation of samples synthesised during 1.5 and 3 hours showed crystalline and well-formed particles with sizes beyond the measurement detection limit (*ca.* 82.9 nm) (see S.5, ESI†).

In contrast, UiO-66-SO₃ and UiO-66-NH₂/SO₃ start with higher correlation lengths that exponentially decrease during the first *ca.* 20 minutes of the reactions (see S.4, ESI†). This could be due to the coordination of Benz-SO₃ to Zr clusters,²³ forming aggregates from which the yolk–shells are formed, as similar starting profiles were recorded for analogue synthesis without the MOFs' linker. After *ca.* 20 minutes, the correlation length increases, reaching its maximum at the beginning of their crystallisation, after which it gradually decreases with no fluctuations despite the changes in crystallisation extent. This could be due to the formation of the yolk–shells structure, in which particle size cannot be detected by the measurement



conditions. In fact, our *ex situ* synthesis shows that at 1.5 hours these samples are composed of yolk-shell structures alongside small nanoparticles, which continue to self-assemble into the final structures during the course of the reaction (see S.5, ESI†).

Increasing the CO₂ adsorption capacity

Among MOFs, zirconium-based frameworks (Zr-MOFs) are particularly attractive for CO₂ capture due to their remarkable water stability. However, their CO₂ adsorption capacity remains limited in comparison with other MOFs such as MOF-74 (Mg).⁶ Different approaches, including defect engineering and linker functionalisation,^{32–34} have been applied to increase the polarity of the MOF and enhance its capacity. Yet, the potential for cooperative adsorption through multiple functionalities remains unexplored,^{7,8,13,14} and the combination of multi-functionalisation with defect engineering has not been studied to enhance CO₂ adsorption. Thus, we propose the multivariate modulation of MOFs as a new one-step pore engineering approach to attach multiple functionalities targeted at CO₂ adsorption at defect sites.

Fig. 3a shows that our defective unfunctionalised UiO-66 exhibited a 2.9 mmol g⁻¹ of CO₂ adsorption capacity at 1 bar at 273 K, which is similar to other reported defective UiO-66 (see S.6, ESI†).³⁵ Modulated UiO-66-NH₂ presented a *ca.* 3.1 mmol g⁻¹ CO₂ adsorption and UiO-66-SO₃ a *ca.* 4.3 mmol g⁻¹ of CO₂, in line with reports showing SO₃ groups enhance CO₂ capacity to a higher extent than NH₂ groups.^{7,8} UiO-66-NH₂/SO₃ presented a CO₂ adsorption of 6.6 mmol g⁻¹ (*ca.* 2.3-fold enhancement compared to the pristine MOF and a 1.6-fold increase compared to UiO-66-NH₂/SO₃), whereas the enhancement was more significant at low pressures (2-fold increase at 0.2 bar compared to UiO-66-SO₃). This effect was maintained at 293 K and for di-modulated MOFs with variable modulators' incorporation, while the enhancement in CO₂ adsorption is minimal upon tuning the modulator content in single-modulated MOFs, confirming the enhancement to be due to cooperativity between functional units (see S.7, ESI†).

Grand canonical Monte Carlo (GCMC)³⁶ simulations were performed on specifically built molecular models representing the molecular formula of *p*-functionalised MOFs to gain deeper insights into the CO₂ adsorption isotherms (see S.8 for detailed methodology, ESI†). While the simulated CO₂ isotherms

matched almost to perfection the experimental isotherms of pristine and single-modulated MOFs (Fig. 3a), the di-modulated UiO-66-NH₂/SO₃ model exhibited a higher adsorption capacity, even at very low pressure. This is likely because the model is not representative for the *ca.* 5 nm regions of missing clusters that UiO-66-NH₂/SO₃ presents, which shall reduce its interactions with CO₂.⁷ Moreover, while our model has SO₃ and NH₂ groups in close proximity, this might not be the case for all modulators in the experimental structures.

Fig. 3b displays the colour-mapped isosurfaces of binding sites of UiO-66 and UiO-66-NH₂/SO₃. Among all the studied MOFs, UiO-66-NH₂/SO₃ has the lowest potential energy, indicating the most favourable binding sites (see S.8, ESI†). The adsorption binding sites of CO₂ are primarily observed around defects. Since -SO₃, and -NH₂, groups are positioned around the defect region, they create a cooperative effect, enhancing CO₂ adsorption: -SO₃ groups introduce strong electrostatic interactions, attracting CO₂ molecules, while -NH₂ groups can engage in dipole-quadrupole interactions with CO₂.

Conclusions

The multivariate modulation of MOFs is a new versatile synthetic method that combines multi-functionalisation and defect engineering in one synthetic step. We have shown how this approach can be applied to engineer the pores of UiO-66 with two functional groups to enhance its CO₂ adsorption capacity by a 2.3-fold due to cooperative effects, which is supported by Monte Carlo simulations. This pore engineering methodology could be applied to other MOF systems and functionalities to enhance the uptake of several gases. We anticipate applicability in diverse areas, as introducing multiple functionalities through defect-engineering offers nearly infinite possibilities, including multiple functional units for the selective adsorption of water contaminants or light-harvesting units, electron and proton transporters for photocatalysis among other possibilities.

Author contributions

IAL conceptualised, designed, and supervised the project, and acquired funding for it. CRM synthesised and characterised the materials. IAL, CRM, MZ, and JCM collected the SAXS data. IAL treated, analysed and interpreted the SAXS data. SJ and MV built MOF models and performed CO₂ adsorption simulations. IAL wrote the first draft of the manuscript with input from all authors.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data for this article, including full characterisation and modelling, will be available at <https://doi.org/10.5281/zenodo.15472541>.

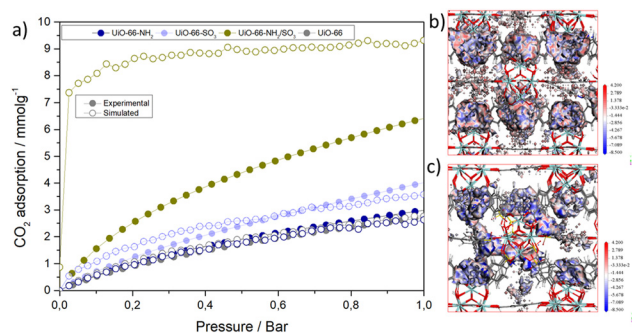


Fig. 3 (a) Experimental and simulated CO₂ adsorption isotherms at 273 K. CMC binding site of (b) UiO-66 and (c) UiO-66-NH₂/SO₃.



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