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Sulfur hexafluoride ( $\text{SF}_6$ ) is a highly potent greenhouse gas (GHG) that is mainly emitted from high-voltage electrical applications. The global warming potential (GWP) of the gas is almost 23 000 times that of  $\text{CO}_2$  and therefore, controlling its emission and recovery is of great importance from both an environmental and economic perspective. Solid adsorbents and adsorption-based technology is a cost-effective and energy-efficient pathway to recapture  $\text{SF}_6$  from its sources, which usually consist of dilute  $\text{SF}_6$  in  $\text{N}_2$ . Here, we present a group of four highly porous and robust gallium- or vanadium-based metal-organic frameworks (MOFs) with exceptional  $\text{SF}_6$  uptake and selectivity. In particular, the novel gallium 1,2,4,5-tetrakis(4-carboxylatephenyl) benzene (TCPB $^{4-}$ ) MOF (Ga-TBAPy) possesses 1-dimensional channels of suitable size ( $5.2 \times 8.4 \text{ \AA}$  and  $5.3 \times 10 \text{ \AA}$ ) to adsorb up to  $2.25 \text{ mmol g}^{-1}$  of  $\text{SF}_6$  at 10 kPa with an excellent  $\text{SF}_6$ -over- $\text{N}_2$  selectivity of 418. Ga-TCPB also exhibits high chemical stability in aqueous and acidic media as well as in organic solvents. 3D electron diffraction (3D ED) patterns combined with high-resolution electron microscopy images were employed to investigate the structure of these water-stable and cyclable MOF  $\text{SF}_6$  adsorbents. Furthermore, this study demonstrates the possibility of using these highly stable MOFs to capture  $\text{SF}_6$  from a gas mixture as well as how MOFs can offer an alternative and efficient way to mitigate the global warming contributions from the emission of  $\text{SF}_6$ .

The rise in global warming and associated climate-related issues has long been connected to the anthropogenic

## Efficient $\text{SF}_6$ capture and separation in robust gallium- and vanadium-based metal-organic frameworks†

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emission of greenhouse gases (GHGs). Six industrially relevant GHGs were specified in the Kyoto Protocol in 1997, namely, carbon dioxide ( $\text{CO}_2$ ), hydrofluorocarbons, methane ( $\text{CH}_4$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), perfluorocarbons, and sulfur hexafluoride ( $\text{SF}_6$ ).<sup>1</sup> While accounting for 76% of the total greenhouse gas emissions,<sup>2</sup>  $\text{CO}_2$  remains the most abundant of the six GHGs. However, the large global warming potential of  $\text{SF}_6$  (22 800 times higher than that of  $\text{CO}_2$ )<sup>3</sup> and its long atmospheric lifetime (3200 years)<sup>4</sup> pose serious concerns. The compound has found wide use (typically in a mixture with  $\text{N}_2$ )<sup>5</sup> in electrical systems, particularly in high-voltage systems and switchgear, as well as in the semiconductor industry, due to its excellent dielectric properties, high stability, and low toxicity.<sup>3</sup> The atmospheric concentration of  $\text{SF}_6$  has, as a consequence, steadily risen in the last 25 years from 3.5 ppt to 11.32 ppt (as of April 2023)<sup>6</sup> due to the growing electricity demands in both developing and developed countries. Sources of  $\text{SF}_6$  emissions were in these places attributed to the handling, leaks, and improper recycling of the gas during maintenance and repair.<sup>7</sup> The recovery, as well as recycling of  $\text{SF}_6$ , particularly from dilute mixtures, is therefore highly important both from an environmental and economic perspective. Adsorption-based processes using solid nanosorbents, such as zeolites,<sup>8,9</sup> porous carbons,<sup>10,11</sup> and metal-organic frameworks (MOFs),<sup>12,13</sup> have shown great promise as a cost-effective and energy-efficient method for GHG capture and separation.<sup>14</sup> MOFs have garnered particular attention in the last couple of decades due to their rich structural diversity, tunable pore size, and surface chemistry which arise from the arrangement of their discrete building units – organic molecules (linkers) and metal ions/clusters (secondary building units).<sup>12,15</sup> Furthermore, the formation of robust MOFs are highly dependent on how these building units are structured and interact – the geometry and rigidity of the organic linkers, the strength of the coordination bonds in the frameworks, as well as the connectivity of the secondary building units.<sup>16–20</sup> MOFs constructed from rod secondary building units (SBUs) encompass an intriguing category of materials that are characterized by their high

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stability, which is partially derived from their topological structure.<sup>16</sup> The infinite SBU chains form framework structures that in many cases possess uniform 1-dimensional channels that may be used for efficient diffusion, separation, and adsorption of guest molecules.<sup>21</sup> A number of rod MOFs have been reported to date. These rod MOFs are based on common divalent transition metals, such as cobalt, zinc, copper, manganese, and nickel (e.g. MOF-74 [ $M_2(C_8H_2O_6)$ ] (where  $M$  denotes the divalent metal cation)<sup>22–25</sup> and MOF-71 [ $Co(C_8H_2O_4)(C_3H_7NO)$ ]<sup>26</sup>), or higher valence metals such as aluminum(III) (e.g. MIL-53 [ $Al(OH)(C_8H_2O_4)$ ]<sup>27</sup> and CAU-10-H [ $Al(OH)(C_8H_2O_4)$ ]<sup>28</sup>), gallium(III) (e.g. MIL-53 [ $Ga(OH)(C_8H_2O_4)$ ]<sup>29</sup> and Ga-fumarate [ $Ga(OH)(C_4H_2O_4)$ ]<sup>30</sup>), and vanadium(III/IV) (e.g. MIL-68 [ $V(OH)(C_8H_2O_4)$ ]<sup>31</sup> and MIL-47 [ $VO(C_8H_2O_4)$ ]<sup>27</sup>). Combining the strong coordinative bonds that emerge between high valence metal cations (such as gallium (Ga)- and vanadium (V)) and carboxylate-based linkers with the topological stability, and the uniform channel arrangements of rod structures, is an effective strategy for constructing MOFs with excellent stability as well as exceptional sorption properties for small guest molecules (e.g.  $H_2O$ ,  $CO_2$ ,  $SO_2$ ).<sup>32–35</sup> Furthermore, introducing rigid and extended linkers into these structures is one approach for building frameworks with increased pore dimensions while retaining the framework's structural and chemical properties. Such moisture-stable frameworks exhibiting high thermal and chemical stability, as well as a high adsorption selectivity for larger guest molecules, are therefore greatly relevant for many industrial applications wherein a sorbent's long-term performance and lifetime are important from an economic perspective. MOF sorbents proposed for  $SF_6$  capture<sup>36–44</sup> have previously

not been shown to exhibit these combined properties. With the aim to construct stable rod MOFs with a suitable pore size for capturing the potent greenhouse gas  $SF_6$ , we synthesized four robust and highly porous MOFs using gallium or vanadium with two different rigid tetratopic linkers (Fig. 1a). Solvothermal reactions between  $VOSO_4 \cdot xH_2O$  or  $Ga(NO_3)_3 \cdot xH_2O$  and  $H_4TBAPy$  or  $H_4TCPB$  in *N,N*-dimethylformamide (DMF) yielded four 3-dimensional porous structures, namely,  $[V_2O_2(TBAPy)]$  (V-TBAPy),  $[V_2O_2(TCPB)]$  (V-TCPB),  $[Ga_2(OH)_2(TBAPy)]$  (Ga-TBAPy), and  $[Ga_2(OH)_2(TCPB)]$  (Ga-TCPB) (Fig. 1b–e and S15–S16, S21†). The crystal structure of the MOFs was determined by 3-dimensional electron diffraction (3D ED) (Fig. S1–S8 and Table S1†). The presence of twinning on Ga-TBAPy prevented the direct determination of the framework structure, however, due to its shared similarities with V-TBAPy, a structure model of Ga-TBAPy was built based on the solved structure of V-TBAPy. In brief, the V(IV) metal ions in V-TBAPy was replaced by Ga(III) ions for Ga-TBAPy, and the entire structure was geometry optimized based on the cell parameters obtained by Le Bail refinement against PXRD data (Fig. S14†) of Ga-TBAPy. Low-dose high resolution transmission electron microscope (HRTEM) images were also collected to verify these structures. As shown in Fig. 1c and S1, S3, S5, and S7,† the pore structures were clearly observed in the HRTEM images and matched well with structure models. The four as-synthesized MOFs crystallized in either a monoclinic  $P2/m$  (V-TBAPy, Ga-TBAPy, and Ga-TCPB) or an orthorhombic  $Pcma$  space group (V-TCPB) with comparable unit cell dimensions aside from unit cell length along the  $c$ -axis (15.638 Å, 16.095 Å, 21.590 Å, and 10.970 Å for V-TBAPy, Ga-TBAPy, V-TCPB, and Ga-TCPB, respectively) (Table S1†). The

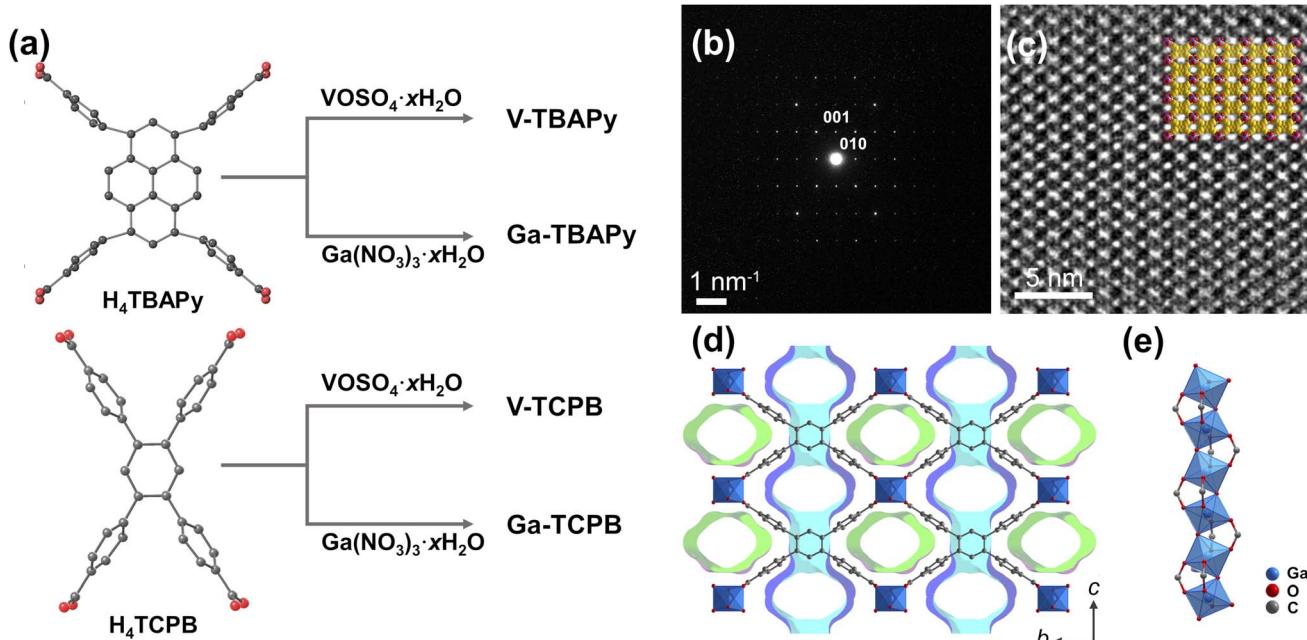


Fig. 1 (a) Synthesis route of Ga- and V-based MOFs with the respective tetratopic  $H_4TBAPy$  and  $H_4TCPB$  ligands, (b) selected area electron diffraction (SAED) image of Ga-TCPB along [100], (c) corresponding HRTEM image with an inset of the crystal structure of Ga-TCPB as viewed along the  $a$ -axis, (d) structure of Ga-TCPB as viewed along the  $a$ -axis showing the presence of two unique pores (colored in green and blue), and (e) the rod SBU running along the  $a$ -axis in the structure.



structure of the MOFs shared similarities with other TBAPy- and TCPB-based framework structures such as ROD-7 ( $[\text{In}_2(\text{OH})_2(\text{-TBAPy})]$ ),<sup>45</sup> ACM-1 ( $[\text{TiO}_2(\text{TBAPy})]$ ),<sup>46</sup> CAU-9 ( $[\text{Al}_2(\text{OH})_2(\text{TCPB})]$ ),<sup>47</sup> and Sc-CAU-9-TCPB ( $[\text{Sc}_2(\text{OH})_2(\text{TCPB})]$ ),<sup>48</sup> which contain rod SBUs consisting of infinite chains of trans corner-sharing octahedra. The Ga(III) and V(IV) metal ions (Fig. S17 and Table S6†) in the structures are coordinated to four different carboxylate groups from the TBAPy<sup>4-</sup> or TCPB<sup>4-</sup> linkers and are connected to adjacent metal ions through two bridging  $\mu_2$ -hydroxide or  $\mu_2$ -oxo groups in the inorganic chain. The resulting frameworks thus possess two types of 1-dimensional rhombohedral channels propagating along [100] (Fig. 1d and S10–S13†) – a larger channel with dimensions of approximately  $5.3\text{--}7.9 \times 9.5\text{--}10 \text{ \AA}$  and a smaller one  $4.9\text{--}5.5 \text{ \AA} \times 8.4\text{--}10 \text{ \AA}$ , as well as narrow pores (approx.  $3.1 \text{ \AA}$ – $3.4 \text{ \AA}$ ) in the [010] direction (taking the van der Waals radii of the atoms into account). The TCPB-based MOFs were found to possess channels of narrower dimensions (approx.  $5.2 \text{ \AA} \times 10 \text{ \AA}$ , Fig. S12–S13†) which are of suitable size to host larger greenhouse gas molecules such as SF<sub>6</sub> (kinetic diameter of  $5.5 \text{ \AA}$ ). The structural stability of the MOF materials in the presence of external stimuli (*e.g.* temperature) and different chemical environments play a pivotal role in their utilization as sorbents in real-life applications, particularly relating to operating conditions and sorbent handling as well as lifetime. The as-synthesized TCPB-

MOFs showed excellent stability in acidic and neutral aqueous media as well as in both protic and aprotic organic solvents at ambient temperatures, while the TBAPy-MOFs were found to be unstable in acidic solutions (Fig. S18 and S19†). The stability of the frameworks is derived from the strong V–O and Ga–O coordinative bonds in the frameworks in conjunction with the shape of the inorganic building units and pore structure. This may in turn lower solvent accessibility, metal–oxygen bond susceptibility for hydrolysis as well as linker dissociation.<sup>49,50</sup> Complete dissolution of the TCPB-based frameworks was only observed in the presence of strong bases such as 0.1 M NaOH. Furthermore, all frameworks also showed high thermal stabilities up to 350 °C and 450 °C for the V- and Ga-based MOFs, respectively (Fig. S20†).

The porosity of the TBAPy- and TCPB-MOFs was confirmed by N<sub>2</sub> sorption at 77 K (Fig. 2a). All four MOFs showed high Brunauer–Emmett–Teller (BET) surface areas between 1107–1484 m<sup>2</sup> g<sup>-1</sup> (Fig. S22–S25 and Table S7†). The density functional theory pore size distributions (DFT-PSD) showed the presence of two types of primary pores as identified by the N<sub>2</sub> isotherms (Fig. S22–S25 and Table S7†) ranging in size from 6.0–8.6 Å and 5.4–7.0 Å in the TBAPy- and TCPB-based MOFs, respectively. Taking into account the errors in the calculated DFT-PSDs, arising from deviations between the utilized DFT model and experimental data, the estimated pore apertures

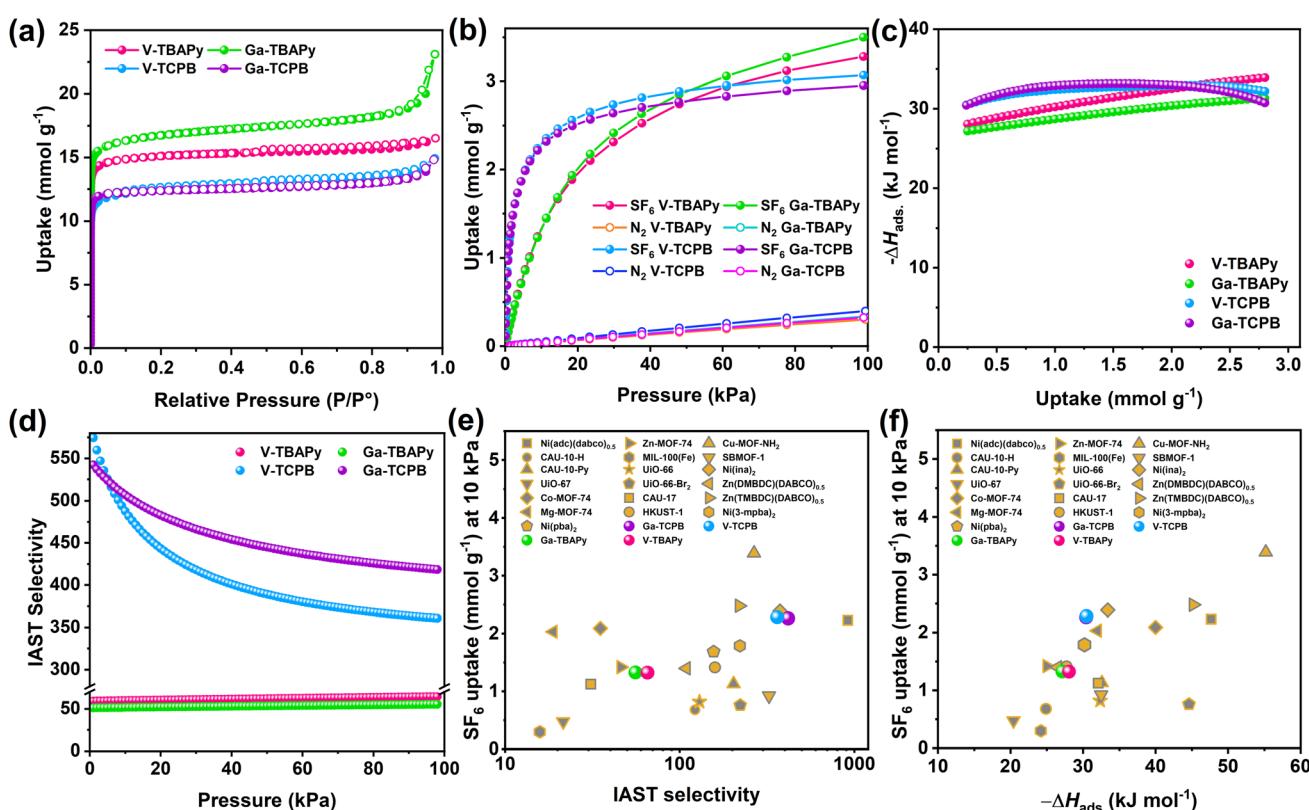


Fig. 2 (a) N<sub>2</sub> sorption isotherms recorded at 77 K (filled and open circles denote the adsorption and desorption branches, respectively), (b) SF<sub>6</sub> and N<sub>2</sub> adsorption isotherms recorded at 293 K, plots of (c) the isosteric enthalpies of SF<sub>6</sub> adsorption ( $-\Delta H_{\text{ads}}$ ), and (d) IAST selectivities, and comparisons between SF<sub>6</sub> uptake capacities at 10 kPa and (e) IAST selectivities, (f)  $-\Delta H_{\text{ads}}$  (at zero or low coverage) of the synthesized TBAPy- and TCPB-MOFs and other porous sorbents.



were comparable with the dimensions of the 1-dimensional channels running along [100] in the crystal structures. The narrow channels along [010] and [001] were not detected due to the kinetic diameter of the  $N_2$  molecules exceeding the size of the pores (approx. 3.0–3.5 Å). The adsorption properties of the TBAPy- and TCBP-MOFs were further investigated using  $SF_6$  and  $N_2$  as well as other well-known greenhouse gases, *i.e.*  $CO_2$ , and  $CH_4$  at pressures up to 100 kPa and at 293 K (Fig. 2b and S26†). All four MOFs showed preferential uptake towards the greenhouse gases, especially  $SF_6$  over  $N_2$ . The  $CO_2$ ,  $CH_4$ , and  $N_2$  adsorption isotherms (Fig. S26†) of the MOFs showed a linear uptake with increasing pressure (2.83–3.49 mmol g<sup>-1</sup>, 0.88–1.38 mmol g<sup>-1</sup>, and 0.30–0.40 mmol g<sup>-1</sup> at 100 kPa, respectively). This observation signifies a moderate to low affinity between the frameworks and the  $CO_2$  as well as  $CH_4$  and  $N_2$  molecules, which indicates that the pore dimensions are unsuitable for the selective capture of these small molecules (<3.8 Å). However, in regards to  $SF_6$ , the TBAPy-based MOFs had the highest  $SF_6$  uptake at 100 kPa of 3.50 mmol g<sup>-1</sup> and 3.28 mmol g<sup>-1</sup> for Ga-TBAPy and V-TBAPy, respectively, followed by 3.07 mmol g<sup>-1</sup> and 2.95 mmol g<sup>-1</sup> for V-TCBP and Ga-TCBP. These numbers correspond well with the overall decrease in pore volume from the TBAPy- to TCBP-based MOFs. Notably, the shape of the  $SF_6$  isotherm over the pressure range differs significantly between the TBAPy- and TCBP-MOFs (Fig. 2b). The TCBP-MOFs adopt Langmuir-shaped isotherms that approach their apparent saturation capacities at lower pressures as compared to the TBAPy-MOFs for which the  $SF_6$  uptake capacities can be observed to steadily increase with pressure. These differences are attributed to the structural dissimilarities between the TBAPy- and TCBP-linkers (Fig. S9†) in which the benzene-core of the TCBP-linker contracts the channel dimensions along [100], resulting in a reduction in pore volume and an increased affinity between the framework and  $SF_6$  molecules. Correspondingly, the  $SF_6$  uptake capacities of the TCBP-MOFs at 10 kPa (2.29 mmol g<sup>-1</sup> and 2.26 mmol g<sup>-1</sup> in V- and Ga-TCBP), were significantly higher than their TBAPy-counterparts (1.33 mmol g<sup>-1</sup> in both V- and Ga-TBAPy). Furthermore, the  $SF_6$  uptakes of Ga- and V-TCBP were comparable to other high-performing MOFs such as Co-MOF-74 (2.09 mmol g<sup>-1</sup>),<sup>38</sup> Ni(adc)(dabco)<sub>0.5</sub> (2.23 mmol g<sup>-1</sup>),<sup>51</sup> and Ni(ina)<sub>2</sub> (2.39 mmol g<sup>-1</sup>)<sup>43</sup> but lower than Cu-MOF-NH<sub>2</sub> (3.39 mmol g<sup>-1</sup>)<sup>44</sup> at 10 kPa and 298 K (Fig. 2e, f and Table S9†). The  $SF_6$  occupancy per unit cell in the MOFs subsequently reached values of 2.59, 2.90, 4.22 and 2.09 for V-TBAPy, Ga-TBAPy, V-TCBP, and Ga-TCBP, respectively, and corresponding  $SF_6$  densities of 860 g L<sup>-1</sup>, 764 g L<sup>-1</sup>, 929 g L<sup>-1</sup>, and 919 g L<sup>-1</sup> which equates to 126–154 times the density of gaseous  $SF_6$  (6.04 g L<sup>-1</sup> at 293 K and 101.325 kPa). The  $SF_6$  occupancy per unit cell for V-TCBP is nearly twice that of Ga-TCBP due to the former MOF crystallizing in a different crystal system and thus possessing a larger unit cell. The  $SF_6$  densities in the MOFs imply a high affinity between the framework and  $SF_6$  molecules as well as efficient packing of the  $SF_6$  molecules in the channels of the structures. The guest–host interaction was further evaluated by their isosteric enthalpies ( $-\Delta H_{ads}$ ) of  $SF_6$  adsorption (Fig. 2c). The  $-\Delta H_{ads}$  at low coverage (*i.e.* 0.24 mmol g<sup>-1</sup>) was

calculated to be 27–30 kJ mol<sup>-1</sup> which is comparable to other proposed  $SF_6$  sorbents (Fig. 2f). The  $-\Delta H_{ads}$  furthermore increased to 31–34 kJ mol<sup>-1</sup> in the TBAPy-based MOFs while it remained comparatively constant (31–32 kJ mol<sup>-1</sup>) in the TCBP-based frameworks as the  $SF_6$  coverage increased to 2.80 mmol g<sup>-1</sup>. This increase in  $-\Delta H_{ads}$  is indicative of growing lateral  $SF_6$ – $SF_6$  interactions which occur as the  $SF_6$  coverage in the channels of the TBAPy-based frameworks increases, while the unchanging  $-\Delta H_{ads}$  imply that the adsorption sites and  $SF_6$ – $SF_6$  interactions in V- and Ga-TCBP are energetically similar.<sup>52–54</sup> Overall the calculated  $-\Delta H_{ads}$  at both low- and high-coverage is moderate but typical for physisorption processes, thus implying that the sorbents may be regenerated at mild conditions.

Differences in guest–host interactions between  $SF_6$  and  $N_2$  molecules are apparent from the adsorption isotherms (Fig. 2b) for which the gradient of the isotherms, as well as the total  $N_2$  uptake capacities (0.30–0.40 mmol g<sup>-1</sup> at 293 K and 100 kPa), are significantly smaller for  $N_2$  as compared to  $SF_6$  and furthermore implies a high adsorption selectivity of  $SF_6$  over  $N_2$ . The Henry's constants ( $K_H$ ) of  $SF_6$  and  $N_2$  (Fig. S30 and Tables S12–15†), which corresponds to the partition of the adsorbate between the adsorbed phase and bulk phase in the Henry's regime (*i.e.* low pressures), show  $SF_6$  values 50 to 400 times higher than that of  $N_2$ . The Henry's law  $SF_6$ -over- $N_2$  ideal selectivities range from 47.5 (Ga-TBAPy), 53.8 (V-TBAPy) to 365 (V-TCBP) and 437 (Ga-TCBP), further indicating the excellent separation performance of, in particular, the TCBP-based MOFs at low pressures. Furthermore, ideal adsorption solution theory (IAST) selectivities of the MOFs were evaluated by considering a gas mixture composed of  $SF_6$ / $N_2$  at a ratio of 10:90. A significant difference between the performance of the TBAPy- and TCBP-based MOFs was observed (Fig. 2d) – the TBAPy-based MOFs exhibited fairly low IAST selectivities of 55 (Ga-TBAPy) and 65 (V-TBAPy) while high selectivities of 361 (V-TCBP) and 418 (Ga-TCBP) were observed for the TCBP-based MOFs at 100 kPa and 293 K. Neither the TBAPy- or TCBP-based MOFs outperform high-performing MOFs such as Cu-MOF-NH<sub>2</sub> (3.39 mmol g<sup>-1</sup>  $SF_6$  uptake at 10 kPa, 298 K and  $SF_6$ / $N_2$  IAST selectivity of 266.2 at 100 kPa)<sup>44</sup> and Ni(adc)(dabco)<sub>0.5</sub> (2.23 mmol g<sup>-1</sup>  $SF_6$  uptake at 10 kPa, 298 K and  $SF_6$ / $N_2$  IAST selectivity of 989.0 at 100 kPa)<sup>51</sup> in terms of  $SF_6$  uptake capacity at 10 kPa nor adsorption selectivity. However, it is crucial to highlight that the combined sorbent properties determine their practical application. Ga-TCBP exhibits a high  $SF_6$  uptake capacity above 2.20 mmol g<sup>-1</sup> at 10 kPa,  $SF_6$ / $N_2$  IAST selectivity greater than 400, and  $-\Delta H_{ads}$  of  $SF_6$  adsorption below 40 kJ mol<sup>-1</sup> indicating a low energy penalty for sorbent regeneration, as well as excellent thermal- and chemical stability in aqueous and acidic environments. These combined properties make Ga-TCBP unique among sorbents reported for  $SF_6$  capture, to our knowledge, and presents it as a highly promising material for  $SF_6$  capture and separation.

Aspects regarding a sorbent's hydrophilic characteristics are also important to consider particularly in regard to handling and for applications using gas mixtures containing water vapor. The TBAPy- and TCBP-based MOFs generally exhibit low water uptake capacities which is attributed to the hydrophobic



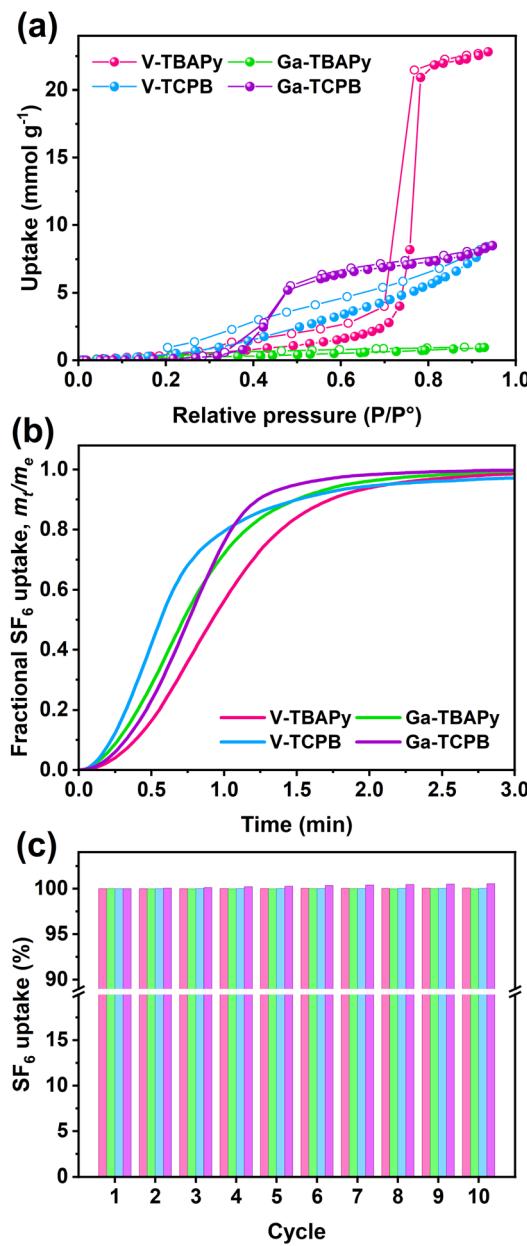


Fig. 3 (a) Water sorption isotherms recorded at 293 K (solid and open spheres represent the adsorption and desorption branches, respectively). (b) gravimetric SF<sub>6</sub> adsorption profiles recorded at 303 K, 100 kPa, and (c) gravimetric SF<sub>6</sub> adsorption cycles.

structure of the TBAPy- and TCBP-linkers (Fig. 3a), in particular, Ga-TBAPy (0.95 mmol g<sup>-1</sup>, 0.02 g g<sup>-1</sup> at  $P/P^0 = 0.93$ ) and V-TCPB (8.40 mmol g<sup>-1</sup>, 0.15 g g<sup>-1</sup> at  $P/P^0 = 0.93$ ) display linear isotherm shapes throughout the partial pressure range. The water sorption isotherms for V-TBAPy (22.81 mmol g<sup>-1</sup>, 0.41 g g<sup>-1</sup> at  $P/P^0 = 0.93$ ) and Ga-TCPB (8.48 mmol g<sup>-1</sup>, 0.15 g g<sup>-1</sup> at  $P/P^0 = 0.93$ ), on the other hand, display a Type V shape which has been observed for other microporous MOFs possessing rod-like SBUs such as CAU-10-H<sup>55</sup> and MIL-53.<sup>56,57</sup> The lack of hysteresis in the sorption isotherms furthermore indicates that the adsorption process in all MOFs proceeds without changes, distortion, or degradation of the

frameworks,<sup>58</sup> further supporting our previous observations that the structures remain stable in humid environments. Adsorption kinetics and sorbent cycling stability are two other parameters that are important to evaluate in order to assess a sorbent's performance. The TCBP-based MOFs were found to display more rapid SF<sub>6</sub> adsorption as compared to their TBAPy counterparts (Fig. 3b) – reaching 80% of their total uptake capacities within 1 min and 1.2–1.4 min, respectively. Furthermore, all MOFs showed excellent recyclability (Fig. 3c) with a negligible decrease in SF<sub>6</sub> uptake capacity from the first cycle to the tenth cycle.

In summary, we have reported on four highly porous gallium- and vanadium-based rod MOFs containing two different tetratopic linkers – TBAPy<sup>4-</sup> and TCBP<sup>4-</sup>. These structures were shown to possess 1-dimensional channels approx. 5.3–7.9 × 9.5–10 Å and 4.9–5.5 Å × 8.4–10 Å in dimensions suitable for SF<sub>6</sub> capture. Structural differences between the TBAPy- and TCBP-based linkers were found to impart a narrower pore size in the V- and Ga-TCPB MOFs. The narrow pores enhanced the affinity between the frameworks and the SF<sub>6</sub> molecules, as compared to the TBAPy-MOFs. In particular, Ga-TCPB exhibited an excellent SF<sub>6</sub> uptake capacity of 2.25 mmol g<sup>-1</sup> at 10 kPa and a high SF<sub>6</sub>/N<sub>2</sub> IAST selectivity above 400. The MOF also displayed a moderately low  $-\Delta H_{ads}$  below 40 kJ mol<sup>-1</sup> which in combination with the great thermochemical stability and recyclability of the material renders it as a highly promising sorbent for SF<sub>6</sub> capture. Utilizing robust rod MOFs containing high valence metals and extended tetratopic linkers to both increase guest–host interactions and framework stability is, to our knowledge, unique among reported SF<sub>6</sub> sorbents, and is a highly promising strategy for constructing materials suited for practical applications.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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