Functionalized metal–organic framework as a new platform for efficient and selective removal of cadmium(II) from aqueous solution†

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In this work, we illustrate how to anchor −SO₃H functional groups onto the pore surface of MOF for cadmium removal from aqueous solution via the approach of sequential post-synthetic modification and oxidation as exemplified in the context of functionalizing the MOF, Cu₃(BTC)₂ with sulfonic acid. The resultant sulfonic acid functionalized MOF, Cu₃(BTC)₂−SO₃H demonstrates a high cadmium uptake capacity of 88.7 mg g⁻¹, surpassing that of the benchmark adsorbents. In addition, it exhibits a fast kinetics with the kinetic rate constant k₂ of 0.6818 g mg⁻¹ min⁻¹, which is 1–3 orders of magnitude higher than existing adsorbent materials for adsorbing cadmium ions from aqueous solution. Moreover, it demonstrates high selectivity of cadmium ions in the presence of other background metal ions, and can be readily regenerated and recycled without significant loss of cadmium uptake capacity. Our work thus paves a way for developing functionalized MOFs as a new type of platform for removing cadmium from wastewater.

1. Introduction

Heavy metal pollution particularly in aqua systems, due to the rapid increase of industrial and mining activities, has become a serious threat to environment and public health.¹ Heavy metal ions, even at low concentrations, are highly toxic to living organisms. Heavy metal ions are non-biodegradable, and they tend to accumulate in the environment thus exerting the negative affect on the environments and ecosystems.²,³ In particular, cadmium is known to directly damage the nervous, reproductive, renal, and skeletal systems, and can also cause some cancers.⁴,⁵ Therefore, the efficient removal of cadmium from wastewater disposed from industrial and mining processes is of urgent need.

A variety of methods for cadmium removal from wastewater have been explored over the past.⁶,⁷ Among those methods, adsorption stands out considering its comparatively low cost, simple design, easy operation, and facile regeneration.⁸,⁹ Various types of sorbent materials, such as carbon materials,¹⁰,¹¹ biomass,¹² magnetic nanoparticles,¹³ and chelating polymers¹⁴ have been extensively investigated for adsorptive removal of cadmium from contaminated water. However, those sorbents face sorts of challenges such as the low surface area, low capacity, moderate affinity/selectivity for Cd(II), which have largely limited their effectiveness and efficiency for the removal of Cd(II) from aqueous solutions. The weaknesses and handicaps associated with existing adsorbents necessitate the development of new types of materials for highly effective and highly efficient removal of Cd(II) from aqueous solutions.

Over the past decade, metal–organic frameworks (MOFs) have emerged as a new type of porous materials and have demonstrated great potential for applications in gas adsorption, gas separation, catalysis, and lithium storage.¹⁵–¹⁹ The employment of MOFs for remove heavy metal ions from aqueous solutions has recently exploited with focus on introducing thio/thiol-functional groups into MOFs for the removal of mercury and lead ions.²⁰–²³ Nonetheless, the exploration of MOFs for cadmium(II) removal particularly selective removal of Cd(II) from other metal ions that remains a challenge to be addressed, has not yet been reported. In this contribution, we illustrate how to anchor the −SO₃H functional groups onto the pore surface of MOF via the approach of sequential post-synthetic modification and oxidation, and the resultant sulfonic acid functionalized MOF demonstrates high uptake capability and fast kinetics for cadmium removal from aqueous solution as well as high selectivity of cadmium ions in the presence of other background metal ions.

2. Experimental section

2.1. Apparatus

A Zeenit 700 atomic absorption spectrometer (Germany) equipped with a flame atomizer was employed for the determination
of cadmium concentration. A cadmium hollow cathode lamp was used as the radiation source at 282.1 nm. Measurements were carried out in the integrated absorbance (peak area) mode at 6 mA, using a spectral bandwidth of 0.2 nm. A Texpert 27 spectrometer (Bruker Co., Germany) was used to obtain Fourier transforms infrared (FTIR) spectra. Powder X-ray diffraction (PXRD) patterns were recorded on a D8 Advance X-ray Diffractometer (Germany) at room temperature. Field emission scanning electron micrographs (SEM) were obtained with a Hitachi S-4800 microscope (Japan) at an acceleration voltage of 15 kV. Specific surface area (BET) was measured by Quantachrome Company NOVA/4000 E physical adsorption instrument automation by N₂ sorption at 77 K.

2.2. Reagents and materials

The cadmium stock solution of 1000 mg L⁻¹ was prepared by dissolving 0.1633 g of CdCl₂·2H₂O in 100 mL deionized water. Working standard solutions of cadmium were prepared by stepwise dilution of the stock solution with deionized water. Copper nitrate, 1,3,5-benzene tricarboxylic acid (H₃BTC, 98%), and other reagents were of analytical reagent grade and obtained from Sinopharm Chemical Reagent Co., Ltd. Double distilled water (18 MΩ cm) was used throughout the experiments.

2.3. Preparation of Cu₃(BTC)₂

The fabrication process was prepared from a typical synthesis method after minor modifications.⁴⁷ 0.2178 g (0.9 m mol) Cu(NO₃)₂·3H₂O was dissolved in 3 mL de-ionized water and mixed with 0.0945 g (0.5 m mol) of H₃BTC dissolved in 6 mL ethanol. The solution was added to a 20 mL Teflon liner, placed in an autoclave, and heated to 393 K for 12 h. The crystals obtained were then filtered, washed with water and ethanol, and dried in 60 °C.

2.4. Preparation of thiol functionalized Cu₃(BTC)₂

The thiol functionalized Cu₃(BTC)₂ were prepared according to the previous report.⁴⁶ 0.1 g as-synthesized Cu₃(BTC)₂ sample was dehydrated at 150 °C for 12 h, and suspended in 10 mL of anhydrous toluene. 1 mL 0.24 mol L⁻¹ dithioglycol solution was then added, and the mixture solution was stirred magnetically for 24 h at room temperature. The solution was filtered, washed by ethanol, and dried in 60 °C. The reaction mechanism diagram was shown in Scheme 1 (ESI†).

2.5. Preparation of sulfonic functionalized Cu₃(BTC)₂

1 g thiol functionalized Cu₃(BTC)₂ sample was dissolved in 50 mL methanol, and sonicated for 10 minutes. 16.3 mL hydrogen peroxide (30%) was added and stirred for 8 hours. Furthermore, the solution was acidified with 0.1 mol L⁻¹ H₂SO₄ for 4 h to ensure complete protonation of all sulfonic acid groups. The resulting crystals were washed by water and ethanol, and dried in 60 °C.

2.6. Adsorption and desorption studies

The adsorption of cadmium by the Cu₃(BTC)₂·SO₃H was investigated using batch equilibrium technique in aqueous solutions, and the pH of the solution was adjusted to 6 with 0.1 mol L⁻¹ HNO₃ or 0.1 mol L⁻¹ NaOH solutions. In general, 10 mg of Cu₃(BTC)₂·SO₃H adsorbent was added to 10 mL of sample solution containing cadmium and shaken at room temperature for 10 min to facilitate adsorption of cadmium onto the sorbent. Desorption was then studied by adding 0.5 mL 0.50 mol L⁻¹ of nitric acid solution to the cadmium-sorbed Cu₃(BTC)₂·SO₃H. After shaking at 200 rpm for 10 min, the Cu₃(BTC)₂·SO₃H were removed and the concentration of cadmium was measured using atomic absorption spectrometer. In order to obtain the adsorption isotherms of the cadmium, solutions with varying initial concentration of cadmium were treated with the same procedure as above at room temperature. The removal efficiency and the amount of heavy metal ions adsorbed q (mg g⁻¹) were given according to the formula:

\[
\text{Removal efficiency (\%)} = \frac{c_0 - c_e}{c_0} \times 100\% \tag{1}
\]

where \(c_0\) and \(c_e\) (mg L⁻¹) are the initial and equilibrium concentrations of cadmium in the solution, respectively.

3. Results and discussion

3.1. Characterization of the sorbent

Given its large surface area, high pore volume, reasonable water/chemical stability, and the accessibility of exposable copper sites for the surface functionalization, we selected Cu₃(BTC)₂ (BTC = 1,3,5-benzenetricarboxylate)⁴⁻²⁵ as a platform to anchor the sulfonic groups that are known to form a stable complex with cadmium ion²⁸ for cadmium removal from aqueous solutions. To introduce sulfonic groups onto the pore surface of Cu₃(BTC)₂, the dithioglycol was first grafted to the open copper sites of the paddle wheel secondary building blocks (SBUs) followed by oxidation of the dangled thiol groups with hydroperoxide (Fig. 1) (hereafter Cu₃(BTC)₂·SO₃H). The successful anchoring of sulfonic groups has been confirmed by FTIR studies, which reveal the appearance of the characteristic
stretching vibration peaks of S–O band\textsuperscript{27,28} between 1000–1350 cm\textsuperscript{-1} Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H compared with Cu\textsubscript{3}(BTC)\textsubscript{2} (Fig. 2a). The preservation of structural integrity after the introduction of sulfonic groups has been verified by the consistence in the powder X-ray diffraction (PXRD) patterns of Cu\textsubscript{3}(BTC)\textsubscript{2} and Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H (Fig. 2b).\textsuperscript{29} PXRD patterns before and after treatment with cadmium solution also indicate that the introduction of –SO\textsubscript{3}H functional groups can improve the water-stability of Cu\textsubscript{3}(BTC)\textsubscript{2}. The SEM image (Fig. S1, ESI\textsuperscript{†}) for Cu\textsubscript{3}(BTC)\textsubscript{2} shows octahedral crystals with smooth surfaces. Although the shape and size of Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H before and after treatment with cadmium solution are similar to Cu\textsubscript{3}(BTC)\textsubscript{2}, the structure of Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H is more loose. The Brunauer–Emmett–Teller (BET) surface areas and pore volumes were derived from nitrogen adsorption isotherms at 77 K and the results are presented in Table 1. Compared with Cu\textsubscript{3}(BTC)\textsubscript{2}, the BET surface area of Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H was reduced to 445 m\textsuperscript{2} g\textsuperscript{-1}, further indicating that successful grafting of –SO\textsubscript{3}H groups on the pore surface of Cu\textsubscript{3}(BTC)\textsubscript{2}.

3.2. Investigation of the effects of pH value in solution on cadmium adsorption and proposed adsorption mechanism

The adsorption of heavy metal ions depends on the pH value of the solution because pH may change the speciation of metal ions and the surface charges of the adsorbent. The obtained zeta potential value of Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H decreased with the increase in solution pH, and the isoelectrical point (IEP) was about 2.1 (Fig. S1, ESI\textsuperscript{†}). Based on these data, the adsorption at pH < 2.1 would be unfavorable for metal cations due to the repulsion with the positively charged surface of the Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H adsorbent. The effect of the initial solution pH on the adsorption of cadmium ions onto Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H composites was then studied in the range of 3.0–8.0 as shown in Fig. 3. The removal efficiency capacity improves with increasing pH values from 3.0 to 6.0. Increasing pH values above 6.0 leads to gradual decrease in the adsorption capacity. At lower pH values (pH < 3.0), protons could occupy most of the adsorption sites on the adsorbent surface, and hence only a low amount of cadmium can be adsorbed due to the competition between protons and cadmium ions. Above pH 6.0, cadmium would precipitate to form hydroxide salts, thus to weaken the interactions between –SO\textsubscript{3}H groups and cadmium ions. Therefore, an optimal pH of 6.0 was selected for all adsorption studies. Fig. 4 illustrates the proposed mechanism for the adsorption of cadmium ions in Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H, which suggests that the metal ions interact with the adsorbent mainly by chelation between the metal ions and the –SO\textsubscript{3}H groups.

### Table 1 BET surface areas and pore volumes of Cu\textsubscript{3}(BTC)\textsubscript{2} and Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Surface area (m\textsuperscript{2} g\textsuperscript{-1})</th>
<th>Pore volume (cm\textsuperscript{3} g\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu\textsubscript{3}(BTC)\textsubscript{2}</td>
<td>627</td>
<td>0.301</td>
</tr>
<tr>
<td>Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H</td>
<td>445</td>
<td>0.300</td>
</tr>
</tbody>
</table>

![Fig. 2 FTIR spectra (a) and PXRD patterns (b) of Cu\textsubscript{3}(BTC)\textsubscript{2} and Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H.](image)

![Fig. 3 Effect of solution pH (red line) and contact time (blue line) on cadmium(II) adsorption in Cu\textsubscript{3}(BTC)\textsubscript{2}–SO\textsubscript{3}H.](image)
3.3. Cadmium adsorption isotherms

To estimate the cadmium(II) uptake capacity of Cu₃(BTC)₂−SO₃H, the adsorption isotherms of cadmium were collected from solutions containing different initial cadmium concentrations (0–200 mg L⁻¹) under the optimized experimental conditions of 10 min-contact time and pH 6.0. The experimental adsorption isotherm data were then fitted with Langmuir and the Freundlich equations to derive the adsorption capacity and affinity of Cu₃(BTC)₂−SO₃H for Cd(II) ions.

The Langmuir isotherm model can be described as the following equation:²⁵

\[
\frac{c_e}{q_e} = \frac{c_e}{q_m} + \frac{1}{q_mK_L}
\]

where \(q_e\) is the amount of cadmium adsorbed on the adsorbent at equilibrium (mg g⁻¹), \(c_e\) is the equilibrium cadmium concentration in the solution (mg L⁻¹), \(q_m\) is the maximum adsorption capacity at monolayer coverage (mg g⁻¹), and \(K_L\) is the Langmuir constant, quantitatively reflecting the affinity of binding sites (L mg⁻¹) to energy of adsorption. The Langmuir model assumes that the solid surface active sites can be occupied only by one layer of adsorbates and that the active sites are independent.

On the contrary, the Freundlich model is based on a heterogeneous adsorption. The Freundlich isotherm is given as:²⁶

\[
\ln q_e = \ln K_F + \frac{1}{n} \ln c_e
\]

where \(q_e\) (mg g⁻¹) and \(c_e\) (mg L⁻¹) have the same definitions as above mentioned. \(K_F\) is the Freundlich constant which indicates the adsorption capacity (L g⁻¹), and \(n\) is an empirical parameter related to the intensity of adsorption.

The relationship between initial cadmium concentration and the adsorption capacity was analyzed using both the Langmuir and Freundlich models (Fig. 5). The calculated correlation coefficient (\(R^2\)) values for each model were shown in Table S1 (ESI†). With respect to the correlation coefficients (\(R^2\) values), the Langmuir isotherm generates a more satisfactory fit to the experimental data than the Freundlich isotherm with the \(R^2\) value greater than 0.998. This suggests that the adsorption of cadmium by Cu₃(BTC)₂−SO₃H is monolayer-type and agrees with the observation that the adsorption from an aqueous solution usually forms a layer on the adsorbent surface.

The maximum uptake capacity (\(q_m\)) for cadmium(II) ions derived from the Langmuir equation is 88.7 mg g⁻¹. To highlight the contribution of –SO₃H groups to cadmium uptake, we compared the adsorption isotherms of parent Cu₃(BTC)₂, Cu₃(BTC)₂−SH, and Cu₃(BTC)₂−SO₃H. Cu₃(BTC)₂−SO₃H outperforms both Cu₃(BTC)₂ and Cu₃(BTC)₂−SH, which exhibit a cadmium uptake capacity of 67.8 mg g⁻¹ and 74.5 mg g⁻¹ respectively despite its lower surface area. The lower cadmium adsorption capacity observed for Cu₃(BTC)₂ could be attributed to that cadmium ions are adsorbed from the solution phase onto the surface of the Cu₃(BTC)₂ by selective complexation with residual carboxyl groups. The introduction of –SH groups, favorable for cadmium binding, on the surface of Cu₃(BTC)₂,

\[
\text{Fig. 4 Proposed mechanism for Cd(II) adsorption in Cu₃(BTC)₂−SO₃H.}
\]

\[
\text{Fig. 5 Langmuir (a) and Freundlich (b) fitting for the adsorption of cadmium onto Cu₃(BTC)₂−SO₃H.}
\]
leads to the improvement of cadmium adsorption capacity. Whereas, an further enhanced has been achieved a
oxidizing the dangled thiol groups into sulfonic groups for Cu3(BTC)2 –SO3H groups can provide multiple binding sites and versatile coordination modes for Cd(II) ions.37,38 It is worth noting that the cadmium uptake capacity of Cu3(BTC)2 –SO3H surpasses that of a series of benchmark sorbent materials (Table 2),13,30–34,39,40 highlighting its potential for application in wastewater treatment.

3.4. Kinetics of cadmium adsorption

It’s known that the adsorption process of heavy metal ions depends on an amalgam of multiple mechanisms such as mass transfer, diffusion control, chemical reactions and particle diffusion. In order to understand the cadmium adsorption kinetics in Cu3(BTC)2 –SO3H, the experimental data collected at the initial cadmium concentration of 1 mg L−1 in pH 6.0 were fitted with the Lagergren pseudo-first-order kinetic model and pseudo-second-order kinetic model.

Table 2 Comparison of cadmium adsorption performances by various adsorbents

<table>
<thead>
<tr>
<th>Sorbent</th>
<th>Adsorption capacity (mg g−1)</th>
<th>Adsorption time (min)</th>
<th>Functionalized groups</th>
<th>Reuse times</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe3O4@APS@AA-co-CA</td>
<td>29.6</td>
<td>45</td>
<td>Carboxyl</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>Sulfonic-functionalized poly (dimethylsiloxane) networks</td>
<td>78.7</td>
<td>1440</td>
<td>Sulfonic</td>
<td>ND</td>
<td>30</td>
</tr>
<tr>
<td>Salicylic acid type chelate</td>
<td>45.0</td>
<td>120</td>
<td>Carboxyl, amine, and hydroxyl</td>
<td>10</td>
<td>31</td>
</tr>
<tr>
<td>Magnetic yeast treated with EDTA dianhydride</td>
<td>48.7</td>
<td>30</td>
<td>Carboxyl, and amine</td>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>PPBM</td>
<td>43.5</td>
<td>100</td>
<td>ND</td>
<td>ND</td>
<td>33</td>
</tr>
<tr>
<td>Si–DTC</td>
<td>40.5</td>
<td>60</td>
<td>Dithiocarbamate</td>
<td>ND</td>
<td>34</td>
</tr>
<tr>
<td>MPG1</td>
<td>87.7</td>
<td>1</td>
<td>Carboxyl</td>
<td>15</td>
<td>39</td>
</tr>
<tr>
<td>ZrO2/B2O3</td>
<td>109.9</td>
<td>30</td>
<td>ND</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>Cu3(BTC)2–SO3H</td>
<td>88.7</td>
<td>10</td>
<td>Sulfonic acid</td>
<td>6</td>
<td>This work</td>
</tr>
</tbody>
</table>

* Fe3O4@APS@AA-co-CA: Fe3O4 magnetic nanoparticles modified with 3-aminopropytriethoxysilane and copolymers of acrylic acid and crotonic acid; PPBM: Portulaca plant biomass; Si-DTC: Silica-supported dithiocarbamate adsorbent; MPG1: magnetic Fe3O4–glycidyl methacrylate–iminodiacetic acid–styrene–divinyl benzene resin; ND: not reported.

The pseudo-first-order and pseudo-second-order kinetic models can be described as: 41,42

\[
\ln \left( \frac{q_e}{q_t} \right) = \ln \left( \frac{q_e}{q_t} \right) - k_1 t \\
\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}
\]

where \(q_e\) (mg g−1) and \(q_t\) (mg g−1) are the amounts of the metal ions adsorbed at equilibrium and at time \(t\) (min), respectively; \(k_1\) (min−1) and \(k_2\) (g mg−1 min−1) are the kinetic rate constants for the pseudo-first-order and the second-order models, respectively. The validities of these two kinetic models are examined and depicted in Fig. 6, and the values of the parameters and the correlation coefficients obtained from these two kinetic models are all listed in Table S2 (ESI†). The results suggest that the cadmium adsorption process in Cu3(BTC)2–SO3H follow the pseudo-second-order kinetic model instead of the pseudo-first-order model. The derived kinetic rate constant \(k_2\) was calculated to be 0.6818 g mg−1 min, which is 1–3 orders of magnitude higher than other adsorbent materials in the cadmium adsorption under similar conditions.32–34,43–47

Fig. 6 Pseudo-first-order (a) and pseudo-second-order (b) models for the adsorption of cadmium onto Cu3(BTC)2–SO3H.
3.5. Desorption of cadmium and recyclability of Cu₃(BTC)₂–SO₃H

Cu₃(BTC)₂–SO₃H can be readily regenerated and recycled, and it can retain more than 85% of the initial cadmium adsorption capacity after six cycles (Fig. 7). The preservation of its structural integrity after six adsorption/elution cycles has been confirmed by powder X-ray diffraction studies as shown in Fig. 8. N₂ isotherms of Cu₃(BTC)₂–SO₃H and Cu₃(BTC)₂–SO₃H after each cycle are shown in Fig. S3 (ESI†). Although the porosity of the Cu₃(BTC)₂–SO₃H was gradually lost in the subsequent adsorption/desorption cycle, the introduction of –SO₃H functional groups onto the pore surface of Cu₃(BTC)₂ can extend the application of water-unstable MOFs in terms of high adsorption capacity and selectivity for cadmium removal. Moreover, the regeneration could be easily achieved by washing the adsorbent with 50 mL deionized water, and then dried at 100 °C in an oven for 0.5 h before use.

3.6. Effect of background ions

Given their coexistence in wastewater, the effect of other metal ions (i.e., Na⁺, Mg²⁺, Ca²⁺, Pb²⁺, Cu²⁺, and Ni²⁺) on cadmium removal efficiency of Cu₃(BTC)₂–SO₃H was assessed. As shown in Fig. 9, Cu₃(BTC)₂–SO₃H can retain its cadmium removal efficiency when various concentrations of metal ions solutions was added in 1 mg L⁻¹ cadmium solution. It is noteworthy that the cadmium removal efficiency only decreased to 95.1% even in the presence of 100 mg L⁻¹ background metal ion solutions. The good selective removal of cadmium is mainly due to the functionalization of SO₃H. In the case of Cu₃(BTC)₂–SH, Pb(II) demonstrated a more significant suppressive effect on cadmium adsorption. The removal efficiency of cadmium obviously decreased to 95.1% with the higher Pb(II) concentrations up to 100 mg L⁻¹. These studies suggest that Cu₃(BTC)₂–SO₃H preferably binds Cd(II) ions over other metal ions, highlighting its potential in selectively removing cadmium from practical wastewater.

4. Conclusions

We have demonstrated the anchoring of –SO₃H functional groups onto the pore surface of MOF for cadmium removal from aqueous solution as exemplified in the context of functionalizing the MOF, Cu₃(BTC)₂ with sulfonic acid via sequential post-synthetic modification and oxidation. The resultant sulfonic acid functionalized MOF, Cu₃(BTC)₂–SO₃H demonstrates high cadmium uptake capacity and fast kinetics for adsorbing cadmium ions from aqueous solution, outperforming the performances of some benchmark adsorbents. In addition, it exhibits high selectivity of cadmium ions in the presents of other background metal ions, and can be readily regenerated and recycled without significant loss of cadmium.
uptake capacity. Our work therefore lays a foundation for developing functionalized MOFs as a new type of platform for removing cadmium from wastewater. Ongoing work in our laboratories includes the design of new MOFs for removing cadmium and other heavy metal ions for water treatment application.

Acknowledgements

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