




## RESEARCH ARTICLE

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# Design of a robust rod-packing scandium–organic framework for C<sub>2</sub>H<sub>x</sub>/CO<sub>2</sub> separation, CO<sub>2</sub> storage, and catalytic CO<sub>2</sub> cycloaddition†

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The exploration of efficient CO<sub>2</sub> capture and conversion techniques is of great importance for global sustainable development. Herein, a novel bi-microporous Sc-MOF, named [Sc<sub>3</sub>(NTB)<sub>2</sub>(CH<sub>3</sub>COO)<sub>3</sub>] (SNNU-616-Sc, NTB = nitrilotribenzoic acid), was successfully designed and utilized for CO<sub>2</sub> storage and catalytic conversion. The linear [Sc<sub>3</sub>(COO)<sub>6</sub>] trinuclear clusters were linked by triple acetate anions into 1D chains, which were further extended by NTB linkers and interleaved to produce the 3D robust rod-packing Sc-MOF with two types of open channels of about 12 Å and 3.8 Å, respectively. Notably, the bare N atom from NTB ligands can not only act as active sites to adsorb CO<sub>2</sub> molecules, but also provide Lewis basic sites for the CO<sub>2</sub> fixation reaction. Together with the high framework stability and two types of microporous open channels, SNNU-616-Sc shows high adsorption selectivity to effectively separate CO<sub>2</sub> from CO<sub>2</sub>–C<sub>2</sub>H<sub>x</sub> binary mixtures (C<sub>2</sub>H<sub>x</sub> = acetylene, C<sub>2</sub>H<sub>2</sub>; ethylene, C<sub>2</sub>H<sub>4</sub>; ethane, C<sub>2</sub>H<sub>6</sub>), and a CO<sub>2</sub> storage capacity of 30 mmol g<sup>-1</sup> (273 K and 29 bar), which surpasses most MOF adsorbents. Moreover, SNNU-616-Sc can also serve as an efficient recyclable catalyst for CO<sub>2</sub> fixation with epoxides in the presence of tetrabutylammonium bromide as a co-catalyst without any organic solvent under mild conditions. Particularly, for the catalytic reaction of CO<sub>2</sub> cycloaddition with epoxide bromopropane, the yields of cyclic carbonates can reach up to 97.5% with the selectivity higher than 98% and a conversion of 99%.

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## Introduction

The greenhouse gas carbon dioxide is the main cause of global warming, and its excessive emissions caused by the combustion of fossil fuel can bring about a series of serious environmental issues, such as extreme weather, ocean acidification, and the greenhouse effect.<sup>1,2</sup> It is extremely critical to develop efficient technologies for the mitigation of CO<sub>2</sub> emission to tremendously reduce the energy crisis and concurrently diminish environmental issues.<sup>3–5</sup> In order to achieve this purpose, many contributions have been made by researchers in various fields in recent years.<sup>6,7</sup>

On the one hand, physical capture technology for CO<sub>2</sub> molecules using porous solid adsorbents and the selective separation of CO<sub>2</sub> from the C<sub>2</sub>-hydrocarbons produced from

industrial manufacture<sup>8–10</sup> have attracted researchers' particular interest, as well as developing a series of materials for selective CO<sub>2</sub> capture and separation from C<sub>2</sub>-hydrocarbons (C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub> and C<sub>2</sub>H<sub>6</sub>).<sup>11–18</sup> On the other hand, to face environmental problems, converting CO<sub>2</sub> to value-added chemical products for CO<sub>2</sub> aftertreatment that can achieve a carbon-neutral energy cycle in the environment has also raised considerable concerns.<sup>2,19</sup> Considering that the multifunctional applications of cyclic carbonates, such as solvents, degreasers, electrolytes in lithium-ion batteries, and precursors for the synthesis of fine chemicals and various polycarbonates,<sup>20,21</sup> adding the excellent properties of stability and low toxic, the conversion of CO<sub>2</sub> into cyclic carbonate becoming the most promising strategies for CO<sub>2</sub> fixation.<sup>22</sup> However, it is challenging to develop efficient, economical, and recyclable heterogeneous catalysts for CO<sub>2</sub> conversion because of the high thermodynamic energy barrier for the inert C=O bond of CO<sub>2</sub> molecules. Summing up the above, developing a kind of efficient CO<sub>2</sub> capture and conversion technique with mild operating conditions and low energy consumption would decrease the global energy demand and carbon emission.

In recent decades, metal–organic frameworks (MOFs), a kind of promising crystalline porous material constructed

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from functionally organic linkers coupled with metal ions/clusters, have drawn much attention due to their high specific surface area, excellent porosity, regular pore systems, good chemical stability, and various topologies.<sup>23–31</sup> Considering the exploitation of new absorbents, MOF materials are undoubtedly used as a candidate to ease the emission of greenhouse gases due to the advantages above and play important roles in catalyzing CO<sub>2</sub> cycloaddition with epoxides in the CO<sub>2</sub> fixation reaction.<sup>32–34</sup>

Given all this, a novel highly stable bi-microporous Sc-MOF (SNNU-616-Sc) with bare Lewis basic nitrogen sites was successfully synthesized to develop efficient CO<sub>2</sub> capture and conversion materials. Thanks to the synergistic effects of extra-stability, open N sites and bi-microporosity, SNNU-616-Sc exhibits top-level CO<sub>2</sub> storage capacity and efficient separation ability for the binary mixture of CO<sub>2</sub>-C<sub>2</sub>-hydrocarbons. Moreover, 1D channels with a size of about 12 Å in this structure can improve the mass transfer rate of the substrate during the catalytic reaction, which makes the SNNU-616-Sc material an efficient recyclable catalyst for CO<sub>2</sub> fixation with epoxides. And the possible reaction mechanism for the catalytic reaction of CO<sub>2</sub> cycloaddition was also discussed.

## Experimental section

### Materials and methods

Sc(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O, nitrilotribenzoic acid (H<sub>3</sub>NTB), *N,N*-dimethylformide (DMF), acetonitrile (CH<sub>3</sub>CN), and acetic acid (CH<sub>3</sub>COOH) were from commercial sources without further purification. Powder X-ray diffraction (PXRD) data were collected on a MiniFlex 600 X-ray diffractometer over the 2θ range of 5–50° using Cu Kα radiation at room temperature. Thermogravimetric analyses (TGA) were carried out in the range of 25–900 °C using an HCT-1 thermal analyzer with a heating rate of 2 °C min<sup>-1</sup> under a N<sub>2</sub> atmosphere. The high pressure gas adsorption performance for CO<sub>2</sub> was analyzed on a BSD-PH high pressure gas sorption analyzer. Gas adsorption isotherms under 1 bar were obtained by using a 3-Flex surface-area and pore-size analyzer, and CO<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>6</sub> and N<sub>2</sub>, and all gases used in the adsorption experiment were of 99.99% purity. Breakthrough experiments were conducted on a home-built dynamic gas breakthrough set-up.

### Synthesis

**Synthesis of [Sc<sub>3</sub>(NTB)<sub>2</sub>(CH<sub>3</sub>COO)<sub>3</sub>] (SNNU-616-Sc).** NTB (9 mg, 0.024 mmol) and Sc(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O (11 mg, 0.048 mmol) were dissolved in a mixed solution of 2 mL DMF and 2 mL CH<sub>3</sub>CN in a 25 mL glass vial, and then 0.5 mL of CH<sub>3</sub>COOH were added to this solution and sealed. After sonication for 10 minutes, the raw materials were completely dissolved to obtain a clear solution, and then the vial was placed into the oven and heated to 120 °C for 6 days. After the temperature dropped to room temperature, yellowish block crystals of SNNU-616-Sc were obtained and washed with fresh DMF. The crystal photo of the optical microscope is shown in Fig. S1.†

### X-Ray single crystal structure determination

The diffraction data of the single crystal sample for SNNU-616-Sc were collected using a Bruker APEX-II CCD with GaKα (λ = 1.34139) radiation at 170 K. The structure was solved and refined by direct methods using the SHELXS program. All non-hydrogen atoms were refined anisotropically. The detailed crystallographic data and the structure refinement parameters of SNNU-616-Sc are summarized in Table S1.† Selected bond lengths and bond angles are given in Table S2.†

### Gas adsorption

Before the measurements of gas adsorption, samples were exchanged with fresh pentane solvent and vacuum heated at 393 K for 10 h to obtain activated MOF samples. In order to evaluate the permanent porosity of SNNU-616-Sc, N<sub>2</sub> adsorption measurements were conducted at 77 K. Gas adsorption measurements of activated samples for single components (CO<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>2</sub>, and C<sub>2</sub>H<sub>6</sub>) at different temperatures (273 K, 283 K, and 298 K) were performed to evaluate the feasibility of SNNU-616-Sc MOF as an adsorbent material to separate CO<sub>2</sub> from the CO<sub>2</sub>-C<sub>2</sub>H<sub>x</sub> mixtures. High pressure gas adsorption performance analysis for CO<sub>2</sub> was conducted at different temperatures to evaluate the storage ability of SNNU-616-Sc.

### Breakthrough experiments

To further verify the actual binary CO<sub>2</sub>-C<sub>2</sub>-hydrocarbon separation performance, breakthrough column experiments were conducted for activated SNNU-616-Sc. About 500 mg of MOF samples were filled in a stainless-steel column (a length of 12 cm, an inner diameter of 0.44 cm, an external diameter of 0.6 cm), and helium was passed with the flow rate of 20 mL min<sup>-1</sup> under ambient pressure at room temperature for 12 h to activate further. Subsequently, a CO<sub>2</sub>-C<sub>2</sub>H<sub>x</sub> (50/50) mixture gas was passed into the column. Before each testing, a helium flow of 30 mL min<sup>-1</sup> had to be maintained for 2–3 h to remove the air and residual gas molecule from the column.

### Catalytic CO<sub>2</sub> cycloaddition

Before the catalytic trials, SNNU-616-Sc was activated at 393 K under high vacuum (10<sup>-6</sup> Torr) for 10 h. The activated-MOF catalyst (20 mg), epoxide substrates (20 mmol), and *n*Bu<sub>4</sub>NBr (32 mg, 0.1 mmol) were placed in a Teflon sample holder inside a stainless-steel reactor. Before the catalytic reactions, the system was filled with CO<sub>2</sub> to get rid of the residual air and then the reactor was sealed and pressurized with CO<sub>2</sub> until 0.8 MPa, and the reactions proceeded at 80 °C for 8 h under stirring. After the catalytic reaction, the reactor was cooled in a water bath, and then ethyl acetate was added into the reactor and the product was taken out. The as-obtained suspension was finally centrifuged to obtain the liquid supernatant and diluted with ethyl acetate. After that, the product was analysed by gas chromatography with a flame ionization detector. For the recycling tests, the supernatant liquid was carefully removed after each catalytic run, and the solid catalyst was

washed with acetone and dried to remove all volatile compounds before reusing for further catalytic cycles.

## Results and discussion

### Structural analysis

Single crystal X-ray diffraction analysis revealed that SNNU-616-Sc crystallizes in the trigonal system, space group  $R\bar{3}$ . Each Sc(III) atom connects six O atoms to form an octahedral coordination model (Fig. 1a), and adjacent three Sc(III) atoms are linked by six carboxylates from six NTB organic linkers to afford a linear  $[\text{Sc}_3(\text{COO})_6]$  trinuclear cluster. As shown in Fig. 1b, each NTB ligand connects three linear trinuclear clusters. Each linear trinuclear motif is bridged by three acetate anions, generating a 1D metal-organic chain (Fig. 1d). Three neighbour 1D chains were further connected by NTB linkers (Fig. 1c) in different directions, and thus interleaved to produce the 3D architecture of SNNU-616-Sc (Fig. 1e and f). Notably, two types of 1D channels with different sizes are observed along the  $c$ -axis direction, which are larger hexagonal and smaller triangular channels with their sizes of about 12 Å and 3.8 Å, respectively (Fig. 1e). Furthermore, the 1D Sc-carboxylate chains can be regarded as rod-like secondary building units, which make SNNU-616-Sc a novel rod-packing metal-organic framework.

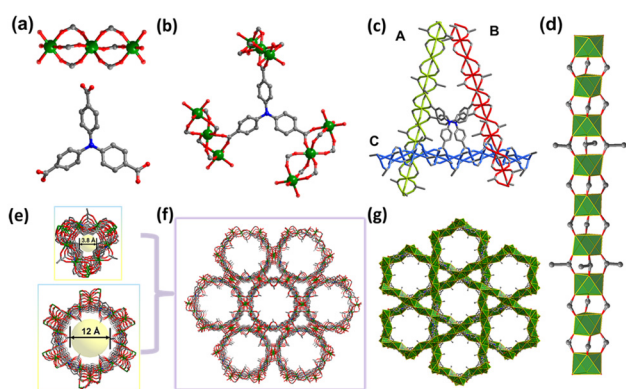
It is noted that the small pore with a size of 3.8 Å is obviously fitting for selective  $\text{CO}_2$  adsorption ( $\text{CO}_2$ ,  $3.18 \times 3.33 \times 5.36 \text{ \AA}^3$ ;  $\text{C}_2\text{H}_2$ ,  $3.32 \times 3.34 \times 5.7 \text{ \AA}^3$ ;  $\text{C}_2\text{H}_4$ ,  $3.28 \times 4.18 \times 4.84 \text{ \AA}^3$ ;  $\text{C}_2\text{H}_6$ ,  $4.08 \times 3.81 \times 4.82 \text{ \AA}^3$ ).<sup>35</sup> Combined with the bare nitrogen atoms as efficient adsorptive sites for  $\text{CO}_2$  molecules, SNNU-616-Sc should be a good candidate for  $\text{CO}_2$  adsorption and separation applications under low pressure. The other pore of about 12 Å is large enough to facilitate not only high-pressure storage for  $\text{CO}_2$ , but also rapid diffusion of molecules inside the pores, which can be expected to offer a confined

space to accelerate the mass transfer and facilitate the catalytic reaction. Clearly, SNNU-616-Sc has great potential as a tri-functional material for  $\text{C}_2\text{H}_x/\text{CO}_2$  separation,  $\text{CO}_2$  storage, and catalytic  $\text{CO}_2$  fixation.

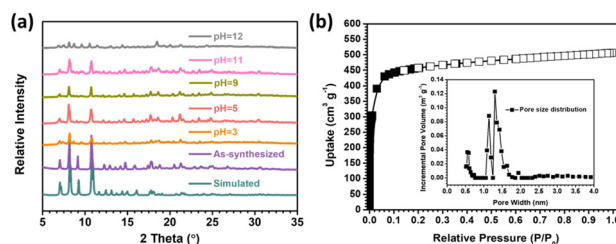
### Stability measurements and porosity characterization

The phase purity of the as-synthesized and activated SNNU-616-Sc MOF samples was confirmed by PXRD measurements (Fig. 2a). The chemical stability was measured by the treatment of MOF samples (30 mg) in solution (10 mL) with different pH values. The PXRD patterns of the as-synthesized and treated MOF samples matched well with the simulated pattern from the data of single crystal X-ray diffraction. These results indicated that SNNU-616-Sc can keep the skeleton intact for more than 48 h in the solutions with a wide pH value range from 3 to 11. The TGA curves (Fig. S2†) showed that the main temperature points of collapse for the SNNU-616-Sc sample before and after solvent exchange were similar. At the very beginning, the weight loss for the solvent-exchanged sample was observed below 373 K because of the loss of solvent molecules. After that, the skeleton was stable up to about 720 K under a  $\text{N}_2$  atmosphere and the framework will collapse over this temperature, which confirms the high thermal stability of SNNU-616-Sc.

$\text{N}_2$  adsorption-desorption isotherms at 77 K confirmed that SNNU-616-Sc has excellent textural properties and exhibits permanent microporosity, as evidenced by reversible type I adsorption isotherms (Fig. 2b). The pore size distributions (PSD) determined by non-local density functional theory (NLDFT) are presented in Fig. 2b (inset). Two main types of pore sizes are observed, which are basically in accordance with the results indicated by the single crystal structure. Moreover, the Brunauer-Emmett-Teller specific surface area calculated from  $\text{N}_2$  adsorption isotherms is  $1398 \text{ m}^2 \text{ g}^{-1}$  and the pore volume is  $0.87 \text{ cm}^3 \text{ g}^{-1}$  for SNNU-616-Sc, which further indicate the great adsorption ability because the adsorption ability of the materials for  $\text{CO}_2$  largely depends on the specific surface area and the micropore volume of the adsorbent.<sup>36</sup> In comparison to the reported MOF materials, the BET surface area of SNNU-616-Sc is less than those of MOF-177 ( $4508 \text{ m}^2 \text{ g}^{-1}$ ),<sup>37</sup> ZJU-195a ( $1722 \text{ m}^2 \text{ g}^{-1}$ ),<sup>38</sup> and MOF-505 ( $1547 \text{ m}^2 \text{ g}^{-1}$ ),<sup>37</sup> and but higher than those of many famous reported MOF materials, such as MIL-53 (Cr) ( $1197 \text{ m}^2 \text{ g}^{-1}$ ),<sup>39</sup> UPC-110



**Fig. 1** The structures of SNNU-616-Sc: (a) the linear  $[\text{Sc}_3(\text{COO})_6]$  trinuclear cluster; (b) the linkage between  $[\text{Sc}_3]$ -clusters and the NTB ligand; (c) the distribution of three 1D chains from different directions; (d) the detailed structure of the 1D chain extended by acetate anions and  $[\text{Sc}_3]$ -clusters; (e) two types of 1D open channels with different sizes; (f) and (g) the 3D framework viewed along the  $c$ -axis direction.



**Fig. 2** (a) PXRD patterns for SNNU-616-Sc after different treatments; (b)  $\text{N}_2$  adsorption-desorption isotherms at 77 K and the pore size distributions for SNNU-616-Sc.

(1384  $\text{m}^2 \text{g}^{-1}$ ),<sup>40</sup> SNNU-45 (1007  $\text{m}^2 \text{g}^{-1}$ ),<sup>41</sup> and NKMOF-1-Ni (382  $\text{m}^2 \text{g}^{-1}$ ).<sup>42</sup>

### Gas adsorption

The single-component gas adsorption experiments for  $\text{CO}_2$ ,  $\text{C}_2\text{H}_4$ ,  $\text{C}_2\text{H}_2$ , and  $\text{C}_2\text{H}_6$  were first conducted at different temperatures to explore the  $\text{CO}_2$  adsorption and separation performance for SNNU-616-Sc. According to Fig. 3, the  $\text{CO}_2$  uptake is 36.3  $\text{cm}^3 \text{g}^{-1}$  at 298 K and 1.0 bar. Under the same conditions, these values for  $\text{C}_2\text{H}_4$ ,  $\text{C}_2\text{H}_2$ , and  $\text{C}_2\text{H}_6$  are 69.6, 76.3, and 77.7  $\text{cm}^3 \text{g}^{-1}$ , respectively. Obviously, SNNU-616-Sc shows much higher uptake capacity for C2-hydrocarbons than for  $\text{CO}_2$ . In addition, the steeper adsorption curves of  $\text{C}_2\text{H}_4$ ,  $\text{C}_2\text{H}_2$ , and  $\text{C}_2\text{H}_6$  in the range of low pressure were reflected in a wide range of temperatures from 273 K to 298 K, which indicate stronger interactions with the MOF skeleton and indicate great potential for the separation of  $\text{CO}_2$  molecules from the C2-hydrocarbons.

The adsorption heat ( $Q_{\text{st}}$ ) in SNNU-616-Sc was further calculated based on the virial equations (eqn (S1) and (S2)†) to evaluate the binding strength between the MOF and gas molecules. The value of adsorption heat for  $\text{CO}_2$  at zero-coverage (20.3  $\text{kJ mol}^{-1}$ ) is much lower than the values of  $\text{C}_2\text{H}_4$  (27  $\text{kJ mol}^{-1}$ ),  $\text{C}_2\text{H}_2$  (28.7  $\text{kJ mol}^{-1}$ ), and  $\text{C}_2\text{H}_6$  (27.5  $\text{kJ mol}^{-1}$ ) (Fig. 4a and S3†). These results indicate stronger interactions with the MOF skeleton for  $\text{C}_2\text{H}_x$  than  $\text{CO}_2$  molecules, which are line with the adsorption curves under lower pressure. In addition, the  $-Q_{\text{st}}$  value at zero-coverage of  $\text{CO}_2$  is less than those of many best  $\text{CO}_2$ -uptake MOFs such as UTSA-74a (25  $\text{kJ mol}^{-1}$ ),<sup>43</sup> NKMOF-1-Ni (40.9  $\text{kJ mol}^{-1}$ ),<sup>42</sup> JCM-1 (33.4  $\text{kJ mol}^{-1}$ ),<sup>44</sup> and JXNU-5 (25.2  $\text{kJ mol}^{-1}$ ),<sup>45</sup> indicating the low regenerative energy consumption of SNNU-616-Sc during the process of recycling.

The ideal adsorbed solution theory (IAST) was applied to calculate the separation performance for binary  $\text{CO}_2$ - $\text{C}_2\text{H}_x$  mixtures. The adsorption isotherms at 298 K were fitted by the

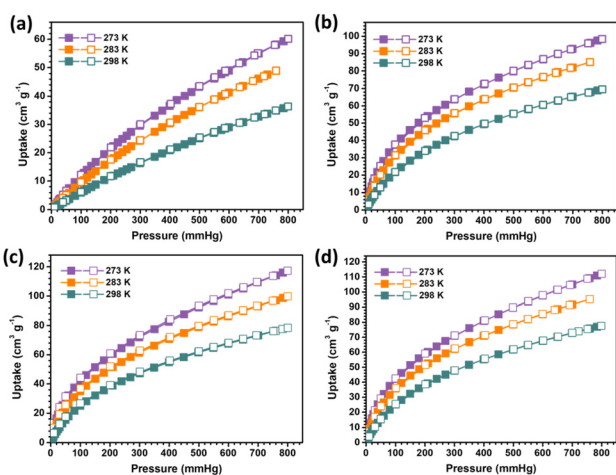


Fig. 3 The gas adsorption isotherms at different temperatures: (a)  $\text{CO}_2$ ; (b)  $\text{C}_2\text{H}_4$ ; (c)  $\text{C}_2\text{H}_2$ ; and (d)  $\text{C}_2\text{H}_6$ .

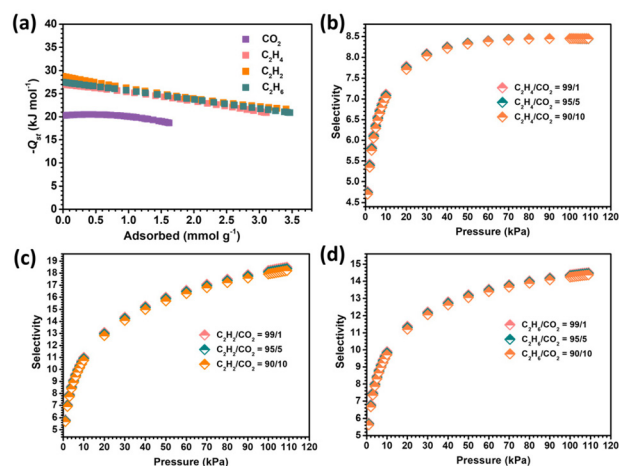
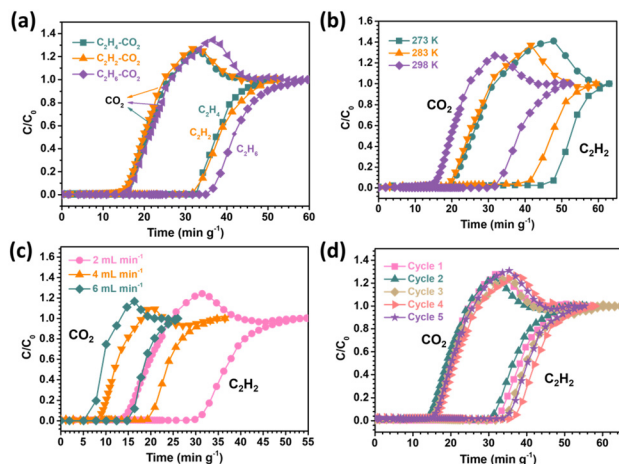


Fig. 4 The calculated adsorption enthalpy for different gases (a), and the IAST separation selectivity at 298 K in SNNU-616-Sc for  $\text{C}_2\text{H}_4/\text{CO}_2$  (b),  $\text{C}_2\text{H}_2/\text{CO}_2$  (c), and  $\text{C}_2\text{H}_6/\text{CO}_2$  (d).

Langmuir-Freundlich equation (eqn (S3)†). As shown in Fig. S4,† the calculated equimolar mixed gas selectivity values of  $\text{C}_2\text{H}_4/\text{CO}_2$ ,  $\text{C}_2\text{H}_2/\text{CO}_2$ , and  $\text{C}_2\text{H}_6/\text{CO}_2$  at 298 K and 1.0 bar are 8.4, 16.5, and 13.5, respectively. The  $\text{C}_2\text{H}_x/\text{CO}_2$  separation ability for different components at 298 K was further calculated (Fig. 4b-d), which shows that with the increase of pressure, the selectivity values increase. This can be attributed to the lateral interactions between  $\text{CO}_2$  molecules that were enhanced as the mixture pressure increased.<sup>46</sup> Particularly, one percent of  $\text{CO}_2$  in the binary mixture of  $\text{C}_2\text{H}_x/\text{CO}_2$  still show good separation selectivity, indicating the excellent ability of removing trace  $\text{CO}_2$  from the  $\text{CO}_2$ - $\text{C}_2\text{H}_x$  mixtures. In general, SNNU-616-Sc has good separation potential to remove  $\text{CO}_2$  from the binary mixture of  $\text{CO}_2$ -C2-hydrocarbons.

### Breakthrough experiments

To confirm the practical separation performance of SNNU-616-Sc for the  $\text{CO}_2$ - $\text{C}_2\text{H}_x$  mixture, breakthrough experiments were conducted. The binary mixture of  $\text{CO}_2$ - $\text{C}_2\text{H}_x$  was injected into a packed column with a flow rate of 2.0  $\text{mL min}^{-1}$  at 298 K to evaluate the separation performance. As depicted in Fig. 5a, the  $\text{CO}_2$  molecule broke through the bed quickly after feeding the gas mixture into the fixed adsorption column, while the detection time for  $\text{C}_2\text{H}_4$ ,  $\text{C}_2\text{H}_2$ , and  $\text{C}_2\text{H}_6$  is later than that of  $\text{CO}_2$  for these three kinds of binary mixtures, showing that the component of C2-hydrocarbons can remain for a longer time in comparison to the  $\text{CO}_2$  molecules in the breakthrough column. According to the breakthrough curves,  $\text{CO}_2$  molecules broke through the column at a time of 14.7  $\text{min g}^{-1}$ , whereas the time for  $\text{C}_2\text{H}_4$ ,  $\text{C}_2\text{H}_2$ , and  $\text{C}_2\text{H}_6$  was retained in the adsorption bed for 32.7, 31.6, and 34.9  $\text{min g}^{-1}$ , respectively, which indicate the stronger interaction between C2-hydrocarbons and the skeleton of SNNU-616-Sc than that of  $\text{CO}_2$ , in line with the results of adsorption enthalpy. And the breakthrough time gaps for these three kinds of binary mixtures ( $\text{C}_2\text{H}_4/\text{CO}_2$ ,  $\text{C}_2\text{H}_2/\text{CO}_2$ ,  $\text{C}_2\text{H}_6/\text{CO}_2$ ) are similar to each other, which indicate an

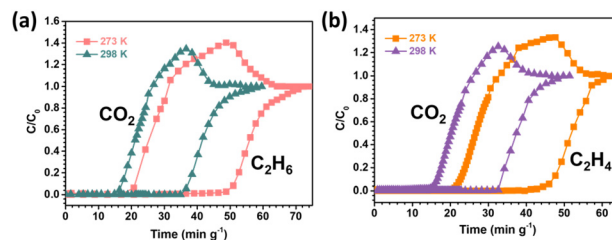


**Fig. 5** Breakthrough curves of SNNU-616-Sc under 1 bar for three equimolar mixtures at 298 K with the flow rate of  $2 \text{ mL min}^{-1}$  (a), the  $\text{C}_2\text{H}_2/\text{CO}_2$  mixture at different temperatures with a flow rate of  $2 \text{ mL min}^{-1}$  (b), the  $\text{C}_2\text{H}_2/\text{CO}_2$  mixture with different flow rates at 298 K (c), and five recycling breakthrough curves for  $\text{C}_2\text{H}_2/\text{CO}_2$  at 298 K with a flow rate of  $2 \text{ mL min}^{-1}$  (d).

excellent separation performance based on the porous adsorbent material SNNU-616-Sc. The actual capture amount of four kinds of gases calculated from the breakthrough curves (eqn (S5) and (S6)†) was 0.89, 1.7, 1.75, and  $1.9 \text{ mmol g}^{-1}$  for  $\text{CO}_2$ ,  $\text{C}_2\text{H}_4$ ,  $\text{C}_2\text{H}_2$ , and  $\text{C}_2\text{H}_6$ , respectively. And the separation factors for  $\text{C}_2\text{H}_4/\text{CO}_2$ ,  $\text{C}_2\text{H}_2/\text{CO}_2$ , and  $\text{C}_2\text{H}_6/\text{CO}_2$  were 1.91, 1.97 and 2.13. Moreover, the purity of the obtained  $\text{CO}_2$  from the three mixtures is above 99.5%.

Moreover, the breakthrough experiments of the  $\text{C}_2\text{H}_2/\text{CO}_2$  binary mixture under different conditions were further conducted to explore the effects of temperature and gas flow rate on the separation performance in actual application. As shown in Fig. 5b, the separation interval time of SNNU-616-Sc for  $\text{C}_2\text{H}_2/\text{CO}_2$  is  $15.8 \text{ min g}^{-1}$  at 298 K and 1 bar, which increases with the decreasing temperature. The separation time is shorter than that of reported materials such as JCM-1,<sup>44</sup> UTSA-74a,<sup>47</sup> and FJU-90a,<sup>48</sup> and comparable to the benchmark ZJUT-2a,<sup>49</sup> and UPC-200(Al)-F-BIM.<sup>50</sup> At 283 K and 273 K, the separation interval times reach  $21.2 \text{ min g}^{-1}$  and  $25.4 \text{ min g}^{-1}$ , respectively. On the other hand, when the flow rate decreases, the separation interval time increases clearly, but when the gas flow rate increases, a shorter separation interval time and smaller transfer mass were observed (Fig. 5c). Even with a flow rate of  $6 \text{ mL min}^{-1}$ , the  $\text{C}_2\text{H}_2/\text{CO}_2$  separation interval time still is about  $10 \text{ min g}^{-1}$ .

Ideal gas adsorbents should have good recyclability in practical industrial applications. Five successive  $\text{C}_2\text{H}_2/\text{CO}_2$  dynamic breakthrough experiments were carried out on SNNU-616-Sc at 298 K and 1 bar with a flow rate of  $2 \text{ mL min}^{-1}$  to evaluate the recyclability. As shown in Fig. 5d, almost constant breakthrough curves indicate its outstanding recyclability and stability. Furthermore, the breakthrough curves at different temperatures for  $\text{C}_2\text{H}_4/\text{CO}_2$  and  $\text{C}_2\text{H}_6/\text{CO}_2$  were also

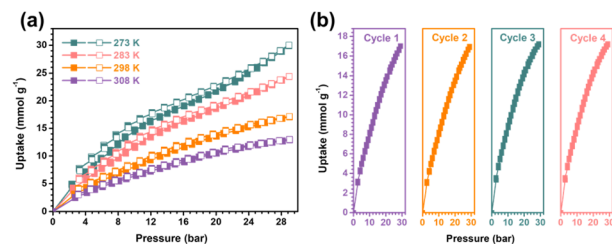


**Fig. 6** The breakthrough curves at different temperatures under 1 bar with the flow rate of  $2 \text{ mL min}^{-1}$  for  $\text{C}_2\text{H}_6/\text{CO}_2$  (a) and  $\text{C}_2\text{H}_4/\text{CO}_2$  (b).

evaluated and are depicted in Fig. 6. Similar to the  $\text{C}_2\text{H}_2/\text{CO}_2$  mixture, the separation interval time increases to about 30 and  $25 \text{ min g}^{-1}$  for  $\text{C}_2\text{H}_6/\text{CO}_2$  and  $\text{C}_2\text{H}_4/\text{CO}_2$  mixtures at 273 K. In our opinion, the smaller triangular channels with a size of  $3.8 \text{ \AA}$  in the structure of Sc-MOF should mainly contribute to the prominent  $\text{C}_2\text{H}_x/\text{CO}_2$  separation performance, which surpasses many famous MOF adsorbents and makes SNNU-616-Sc a great adsorbent for practical separation in industrial applications.

### High-pressure $\text{CO}_2$ storage

The single-component  $\text{CO}_2$  adsorption isotherm of SNNU-616-Sc has no tendency of gentle curve in comparison to the other three C2-hydrocarbon gases from 0 to 1 bar, which indicates that SNNU-616-Sc may be can adsorb much more  $\text{CO}_2$  under higher pressure. At the same time, taking the high BET specific surface area ( $1398 \text{ m}^2 \text{ g}^{-1}$ ) and larger pore size of 1D hexagonal channels ( $12 \text{ \AA}$ ) into account, SNNU-616-Sc should be more propitious to high-pressure  $\text{CO}_2$  storage. High-pressure  $\text{CO}_2$  adsorption results at different temperatures for SNNU-616-Sc show that the storage capacity can reach as high as  $30 \text{ mmol g}^{-1}$  ( $672.2 \text{ cm}^3 \text{ g}^{-1}$  and 48.8 wt%) at 273 K and 29 bar (Fig. 7a and Table S4†), which is slightly lower than the performance of MFM-160a ( $32 \text{ mmol g}^{-1}$ , 19.8 bar) and superior to most MOFs reported at 273 K (Fig. S7†), such as MIL-125-Ti ( $10.761 \text{ mmol g}^{-1}$ , 9.8 bar),<sup>51</sup>  $\beta$ -Zn ( $8 \text{ mmol g}^{-1}$ , 28 bar),<sup>52</sup> MIX-MIL-125-Ti ( $7.71 \text{ mmol g}^{-1}$ , 9.8 bar),<sup>51</sup> MOF-74-Mg ( $\sim 7 \text{ mmol g}^{-1}$ , 30 bar),<sup>53</sup> MFC-1 ( $6.7 \text{ mmol g}^{-1}$ , 30 bar),<sup>53</sup> MIL-100-Fe ( $0.62 \text{ mmol g}^{-1}$ , 30 bar),<sup>53</sup> and MMC1 ( $\sim 0.6 \text{ mmol g}^{-1}$ , 30 bar).<sup>53</sup> At room temperature, SNNU-616-Sc still can take up  $\text{CO}_2$  of  $17.1 \text{ mmol g}^{-1}$  ( $384.3 \text{ cm}^3 \text{ g}^{-1}$ , 29 bar), which was competitive with many famous MOFs under the same con-



**Fig. 7** The high-pressure  $\text{CO}_2$  adsorption-desorption curves at different temperatures (a) and the recyclability results (b) at 298 K.

ditions like MOF-505 (18 mmol g<sup>-1</sup>, 30 bar),<sup>37</sup> MIL-101-Cr (14.38 mmol g<sup>-1</sup>, 40 bar),<sup>54</sup> MIL-53-Cr (10.6 mmol g<sup>-1</sup>, 25 bar),<sup>39</sup> and MIL-53-Al (9.5 mmol g<sup>-1</sup>, 25 bar).<sup>55</sup> Besides, SNNU-616-Sc displays excellent reusability for CO<sub>2</sub> storage under at least five regeneration conditions (Fig. 7b).

### GCMC simulations

GCMC simulations were further adopted for SNNU-616-Sc to investigate the probable adsorption sites of CO<sub>2</sub> and C<sub>2</sub>-hydrocarbons in the MOF skeleton. As shown in Fig. S8,† the probable sites of CO<sub>2</sub> molecules in SNNU-616-Sc are mainly distributed in triangular channels with a suitable pore size, and the second sites are distributed in the surroundings of the N atom sites from the NTB ligands. SNNU-616-Sc shows three same binding site distribution toward C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, and C<sub>2</sub>H<sub>6</sub>, in which the first two adsorptive sites are the same as for CO<sub>2</sub> molecules. The third sites are within the larger hexagonal channels. So, the number of adsorptive sites for C<sub>2</sub>-hydrocarbons is clearly more than those for CO<sub>2</sub> molecules in the structure of SNNU-616-Sc, combined with the suitable pore volume and the higher strength of the interaction between C<sub>2</sub> hydrocarbons and the skeleton than the CO<sub>2</sub> molecules, and further supports the efficient separation performance of CO<sub>2</sub> molecules from C<sub>2</sub>H<sub>2</sub>/CO<sub>2</sub> mixtures.

The difference in the interactions between guest molecules and the MOF skeleton in the SNNU-616-Sc may arise from the Lewis basic bare N sites. The binding sites of CO<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>2</sub> and C<sub>2</sub>H<sub>6</sub> were further evaluated by modelling studies. The distances of C–H...N for C<sub>2</sub>-hydrocarbons (C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>2</sub>, and C<sub>2</sub>H<sub>6</sub>) and O=C...N for CO<sub>2</sub> molecules were obtained. As given in Fig. 8, the O=C...N distance for CO<sub>2</sub> molecules (5.05 Å) is markedly longer than the C–H...N distances for C<sub>2</sub>-hydrocarbons (C<sub>2</sub>H<sub>4</sub>, 4.4 Å; C<sub>2</sub>H<sub>2</sub>, 4.98 Å; C<sub>2</sub>H<sub>6</sub>, 4.19 Å), showing stronger interactions of C<sub>2</sub>-hydrocarbons than CO<sub>2</sub>, which also



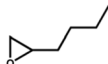





offers theoretic support for the effective CO<sub>2</sub>-C<sub>2</sub>-hydrocarbon separation performance.

### Cycloaddition of CO<sub>2</sub> with epoxides

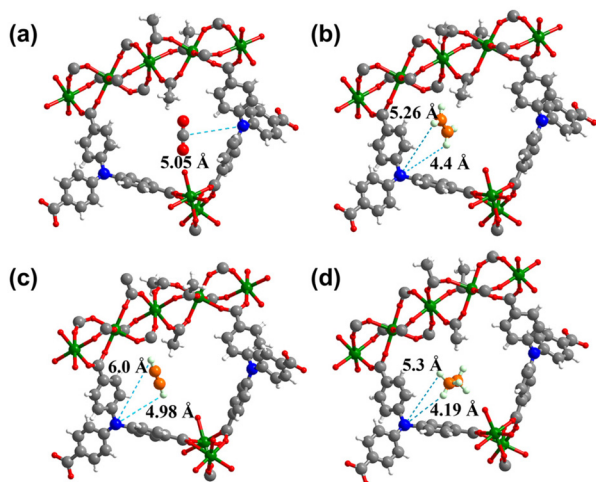
The prominent CO<sub>2</sub> adsorption and separation performances of SNNU-616-Sc encourage us to further investigate the catalytic activity for cycloaddition of epoxides with CO<sub>2</sub>. Accordingly, a series of epoxide substrates were examined for the synthesis of the corresponding cyclic carbonates in the presence of SNNU-616-Sc as a catalyst at 0.8 MPa CO<sub>2</sub> pressure and 353 K (Table 1). As for entry 1 to entry 3, epoxides with alkyl chains of different lengths were used as substrates for the reaction, and the yields of epoxypropane, epoxybutane, and epoxy hexane were 95.8%, 94.2%, and 73.6%, respectively. Among them, epoxy hexane with the longest alkyl chain showed the lowest yield, which indicated that the catalytic activity of the cycloaddition reaction declined with the increase of steric hindrance. So, the effective size of the epoxides is necessary to facilitate their entrance into the channel to close the catalytically active sites. Only 74.6% of epoxy hexane was converted due to its difficult diffusion into the pores of the catalyst, and the difficulty of ring opening due to the large steric hindrance of the benzene ring hindering the Br<sup>-</sup> attack also resulted in its low conversion. Moreover, SNNU-616-Sc exhibits highly efficient catalytic activity with a yield of 97.5% in carbonate formation after 8 h with 99% conversion and 98.6% selectivity when epoxide bromopropane was used as a reactant in the presence of *n*Bu<sub>4</sub>NBr as a co-catalyst (Table 1, entry 5).

The blank experiment (entry 6) by only adding the cocatalyst *n*Bu<sub>4</sub>NBr was conducted under the same conditions without SNNU-616-Sc, and the yield of cyclic carbonates is only

**Table 1** Catalytic performance of SNNU-616-Sc for the CO<sub>2</sub> cycloaddition reaction with different epoxides

No	Substrate	PCO <sub>2</sub> (MPa)	T (°C)	t (h)	Yield (%)	Con. (%)	Select. (%)
1		0.8	80	8	95.8	97.2	95.6
2		0.8	80	8	94.2	99.9	94.3
3		0.8	80	8	73.6	74.6	94.2
4		0.8	80	8	90.2	92.3	97.7
5		0.8	80	8	97.5	99	98.6
6 <sup>a</sup>		0.8	80	8	52.5	47.5	98.8
7 <sup>b</sup>		0.8	80	8	74.0	81.9	90.4
8 <sup>c</sup>		0.8	80	8	37.7	36.7	99.8

Reaction conditions: epoxide = 20 mmol; catalyst = 20 mg SNNU-616-Sc; *n*Bu<sub>4</sub>NBr = 0.1 mmol, 32 mg; semi-batch reaction; determined by GC. <sup>a</sup> Without a catalyst. <sup>b</sup> Catalyst = Sc(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O. <sup>c</sup> Catalyst = NTB ligand.



**Fig. 8** The binding sites between bare N sites and CO<sub>2</sub> (a), C<sub>2</sub>H<sub>4</sub> (b), C<sub>2</sub>H<sub>2</sub> (c) and C<sub>2</sub>H<sub>6</sub> (d) molecules calculated by modelling studies for SNNU-616-Sc.

52.5% with a low conversion rate of 47.5%, indicating that  $n\text{Bu}_4\text{NBr}$  played an important role in ring opening, but it is deemed insufficient in improving the catalytic activity due to the lack of sufficient catalytic sites and mass transfer channels of the substrate. From the entries 5 and 6,  $\text{Sc}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$  metal salts or NTB ligands are used as catalysts added to the reaction in the presence of  $n\text{Bu}_4\text{NBr}$ , which shows clearly lower catalytic activity in comparison to the SNNU-616-Sc MOF catalyst. Therefore, the catalytic sites and mass transfer channels are of great significance in the catalytic reactions of  $\text{CO}_2$  cycloaddition.

Recyclability is a critical criterion for an effective heterogeneous catalysis. The cycling experiments for epoxide bromopropane were also conducted under the same conditions (80 °C, 8 h, 0.8 MPa of  $\text{CO}_2$  pressure) after easy separation and a simple filtration for SNNU-616-Sc, and washed several times with acetone. Fig. 9a shows that the recycled MOF catalyst can be reused up to at least five consecutive times without any considerable activity attenuation, showing an excellent recyclability. Moreover, the regenerative SNNU-616-Sc catalyst was analysed by PXRD. The PXRD patterns for the fresh MOF and recovered catalyst after 5 cycles are in full agreement with each other, further supporting the extraordinary catalytic stability of the SNNU-616-Sc catalyst (Fig. 9b).

Temperature-programmed desorption (TPD) of  $\text{CO}_2$  and  $\text{NH}_3$  analysis were performed to investigate the acid–base nature of the catalyst. As shown in Fig. S9,† SNNU-616-Sc shows an obvious peak at about 523 K for TPD- $\text{CO}_2$ , and TPD- $\text{NH}_3$  has very little peaks over the whole range of temperatures, indicating the presence of strong basic sites in this structure and almost no acidic sites in the catalyst. The results of TPD analyses confirmed that the SNNU-616-Sc catalyst offers strong basic sites for the  $\text{CO}_2$  cycloaddition catalytic reactions.

### Cycloaddition reaction mechanism

Based on the single crystal structure,  $\text{CO}_2$  adsorption and catalytic  $\text{CO}_2$  cycloaddition of SNNU-616-Sc with epoxides, a plausible catalytic reaction mechanism was proposed.<sup>56</sup> As shown in Fig. 10, in the first step, the bare N sites with lone pair electrons acted as Lewis basic sites to activate  $\text{CO}_2$  molecules. In the second step,  $\text{Br}^-$  anions generated from the co-catalyst

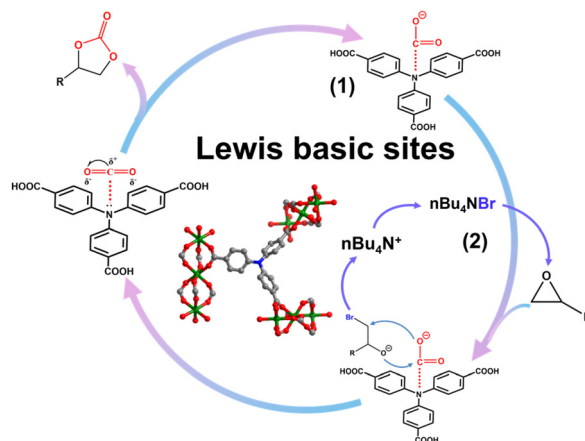


Fig. 10 The proposed catalytic mechanism of SNNU-616-Sc for  $\text{CO}_2$  cycloaddition.

attack the less hindered C atom of the coordinated epoxides, followed by a ring-opening step. Thereafter, activated  $\text{CO}_2$  interacts with the oxygen anion of the opened epoxy ring, forming an alkyl carbonate anion, and the corresponding cyclic carbonate is generated through ring closure with the elimination of the bromide ion. So, the good catalytic performance of SNNU-616-Sc is believed to be attributed to the synergistic effect of the basic catalytic sites and large mass transfer 1D channels in the presence of  $n\text{Bu}_4\text{NBr}$ .

## Conclusions

In this work, a robust rod-packing Sc-MOF with two types of micropores and Lewis basic bare N atoms was synthesized and utilized for  $\text{CO}_2$  adsorption and conversion. Benefitting from the synergistic effects of high chemical and thermal stability, bi-microporous open channels, and bare N sites, the Sc-MOF exhibits not only a prominent separation ability of  $\text{CO}_2$  from  $\text{C}_2\text{H}_x\text{-CO}_2$  binary mixtures, but also an extra-high  $\text{CO}_2$  storage capacity. Remarkably, the Sc-MOF also can act as an excellent catalyst for  $\text{CO}_2$  cycloaddition with epoxides with high productivity, prominent selectivity, and good recyclability. In general, we offer a helpful route to explore novel CCS materials with high  $\text{CO}_2$  adsorption and conversion performance under mild conditions, which are critical for the global energy demand and carbon emission.

## Author contributions

Hong-Juan Lv: methodology, data collection and analysis, and writing the original draft. Shu-Cong Fan: investigation and data analysis. Yu-Cheng Jiang: formal analysis. Shu-Ni Li: investigation and resources. Quan-Guo Zhai: supervision, checking & editing, and funding acquisition.

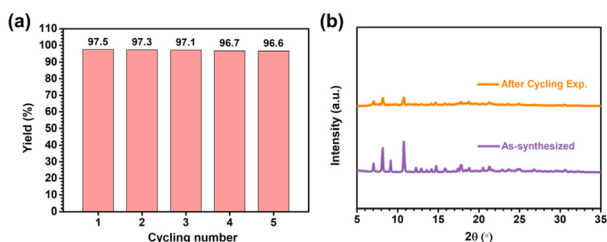


Fig. 9 (a) The yield of epoxide bromopropane for five catalytic cycles; (b) PXRD patterns for SNNU-616-Sc samples after the  $\text{CO}_2$  cycloaddition reactions.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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