

Cite this: *Mater. Adv.*, 2021,  
2, 3685

# Elucidating the role of non-covalent interactions in unexpectedly high and selective CO<sub>2</sub> uptake and catalytic conversion of porphyrin-based ionic organic polymers†

Sinem T. Kostakoğlu,<sup>a</sup> Yurii Chumakov,<sup>bc</sup> Yunus Zorlu,<sup>id a</sup> Ali E. Sadak,<sup>id d</sup>  
Serpil Denizaltı,<sup>id e</sup> Ayşe G. Gürek<sup>id a</sup> and Mehmet M. Ayhan<sup>id \*a</sup>

Here, we present viologen-porphyrin based ionic covalent organic polymers (**H2-ICOP** and **Zn-ICOP**) with multiple CO<sub>2</sub>-philic sites. The specific surface areas of **H2-ICOP** and **Zn-ICOP** were found to be 9 m<sup>2</sup> g<sup>-1</sup> and 20 m<sup>2</sup> g<sup>-1</sup>, respectively. CO<sub>2</sub> uptake analyses reveal that **H2-ICOP** exhibits very high CO<sub>2</sub> capture uptake (62.9 mg g<sup>-1</sup>), which is one of the highest values among previously reported ICOPs. The results indicate very efficient non-covalent interactions between **H2-ICOP** and CO<sub>2</sub>. The possible non-covalent interactions of hydrogen (O<sub>CO<sub>2</sub></sub>...H-N), tetrel (C<sub>CO<sub>2</sub></sub>...N, C<sub>CO<sub>2</sub></sub>...Cl<sup>-</sup>), pnictogen (O<sub>CO<sub>2</sub></sub>...N<sup>+</sup>), and spodium bonds (O<sub>CO<sub>2</sub></sub>...Zn) between CO<sub>2</sub> and **H2-ICOP** and **Zn-ICOP** are investigated via symmetry adapted perturbation theory (SAPT) analysis and electrostatic potential maps (MEP). The strength of non-covalent interactions in **H2-ICOP** and **Zn-ICOP** is decreasing in the following order  $\Delta E_{C...N} > \Delta E_{C...Cl^-} > \Delta E_{O...N^+}$  and  $\Delta E_{Zn...O} > \Delta E_{C...Cl^-} > \Delta E_{C...N} > \Delta E_{O...N^+}$ , respectively. The major CO<sub>2</sub> uptake contribution comes from C<sub>CO<sub>2</sub></sub>...N tetrel bonding (−22.02 kJ mol<sup>-1</sup>) interactions for **H2-ICOP**, whereas O<sub>CO<sub>2</sub></sub>...Zn spodium bonding (−21.065 kJ mol<sup>-1</sup>) interactions for **Zn-ICOP**. **H2-ICOP** has more CO<sub>2</sub>-philic moieties with powerful non-covalent interactions compared to **Zn-ICOP**, which is in good agreement with the experimental results. Furthermore, the CO<sub>2</sub> catalytic conversion performances of **Zn-ICOP** and **H2-ICOP** gave good yields of 83% and 54%, respectively. Surprisingly, **Zn-ICOP**, despite having significantly lower CO<sub>2</sub> uptake capacity, displayed better catalytic activity than **H2-ICOP**, owing to a higher number of counter anions (Cl<sup>-</sup>) on its surface, which shows the crucial role of the counter anion (Cl<sup>-</sup>) in the mechanism of this catalytic reaction.

Received 11th March 2021,  
Accepted 11th April 2021

DOI: 10.1039/d1ma00217a

rsc.li/materials-advances

## 1. Introduction

The rise of the atmospheric carbon dioxide (CO<sub>2</sub>) concentration has become a widespread concern due to its link to the greenhouse effect and threat to the environment.<sup>1</sup> Therefore, viable solutions for efficient capture and utilization of CO<sub>2</sub> (CCU) have received much attention in the past decades.<sup>2,3</sup> Among various CO<sub>2</sub> removal technologies, physical adsorbents such as zeolites,

metal–organic frameworks (MOFs), covalent organic frameworks (COFs) and porous covalent organic polymers (COPs) came into focus owing to their high CO<sub>2</sub> capture capacities, catalytic transformation, and low energy requirements for regeneration.<sup>4–8</sup> Especially COPs have evolved for CCU due to their high specific surface areas, easily tunable pore structures, good chemical and thermal stabilities, tailored surface manipulation with polar groups, and variation in the synthesis.<sup>9–13</sup>

A high selective uptake of CO<sub>2</sub> is known to arise from large surface areas and non-covalent interactions between CO<sub>2</sub> and surfaces of materials. In the past decade, significant effort has been mainly focused on increasing the surface areas of materials and the non-covalent interactions between CO<sub>2</sub> and surfaces of materials have not attracted enough attention.<sup>14</sup> One should note that a large surface area is one of the parameters, but not the only one, that allows for high CO<sub>2</sub> capture. However, materials with a low surface area may still exhibit large CO<sub>2</sub> capture capacity with efficient non-covalent interactions with CO<sub>2</sub>. Therefore, it is vitally important to identify and estimate the strength of these non-covalent interactions in terms of the contribution to the

<sup>a</sup> Gebze Technical University, Department of Chemistry, Kocaeli, 41400, Turkey.

E-mail: menafayhan@gtu.edu.tr

<sup>b</sup> Gebze Technical University, Department of Physics, Kocaeli, 41400, Turkey<sup>c</sup> Institute of Applied Physics, MD-2028, Chisinau, Moldova<sup>d</sup> TUBITAK UME, Chemistry Group Laboratories, TR-41470, Gebze-Kocaeli, Turkey<sup>e</sup> Ege University, Department of Chemistry, Bornova, İzmir, Turkey† Electronic supplementary information (ESI) available: Synthesis and analysis details; photographs of gel-like or powder ICOPs; FTIR of **H2-ICOP-dx** and **Zn-ICOP-dx**; CP/MAS <sup>13</sup>C-NMR; PXRD with simulated patterns, EDS, DLS and zeta potentials for **H2-ICOP** and **Zn-ICOP**; SEM images of **H2-ICOP-dx** and **Zn-ICOP-dx**; formation of simultaneous tetrel bonds in **H2-ICOP** and **Zn-ICOP**; SAPT results for the interaction between two CO<sub>2</sub> molecules placed at the same porphyrin fragments in **H2-ICOP** and **Zn-ICOP**. See DOI: 10.1039/d1ma00217a

CO<sub>2</sub> capture capacity.<sup>15,16</sup> CO<sub>2</sub> is known to be able to form simultaneous non-covalent interactions *via* its electron-rich terminal oxygen atoms and its electron-deficient central carbon atom.<sup>16,17</sup> The electron-deficient central carbon atom acts as a Lewis acid (LA) and can form tetrel bonding interactions with anions or lone-pair-possessing atoms such as N, O, S, and F.<sup>18–21</sup> On the other hand, the electron-rich terminal oxygen atom acts as a Lewis base (LB) and can form hydrogen bonding with hydrogen atoms and, as recently reported, halogen bonding with halogen atom (I, Br, Cl) containing moieties.<sup>22–29</sup>

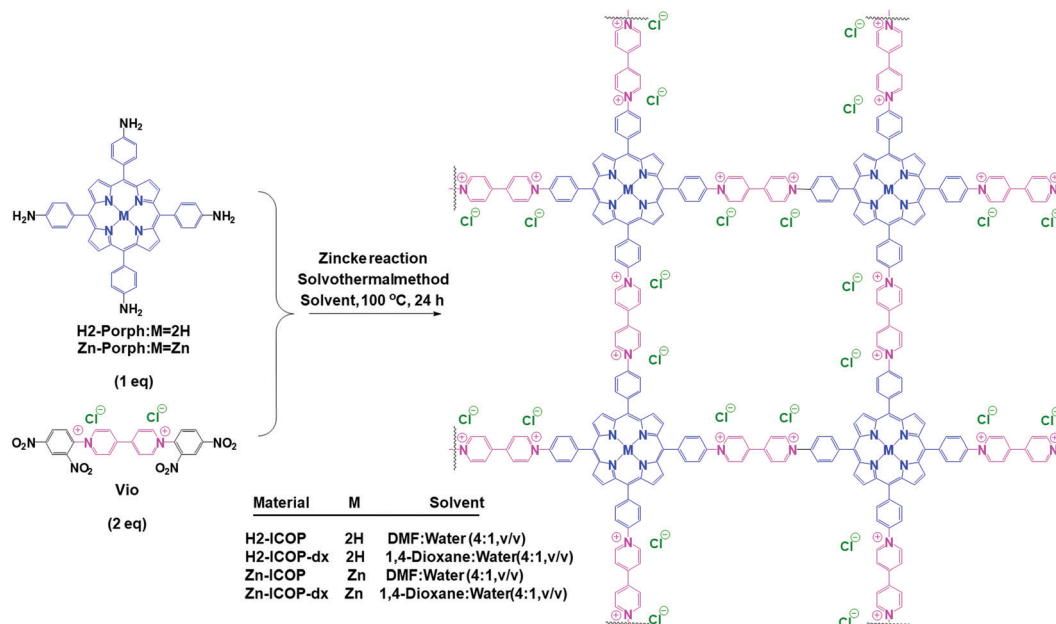
In particular, electron-rich nitrogen-based functional groups, such as amines, triazoles, triazine cores, imines, tetrazoles, benzimidazoles, azo linkages, and viologens, continue to be a dominant polar functional group to enhance the CO<sub>2</sub> adsorption capacity and CO<sub>2</sub>/N<sub>2</sub> selectivity thanks to their multiple non-covalent interactions with CO<sub>2</sub>.<sup>20,27,30–38</sup> Among nitrogen based adsorbents, viologen linked ionic covalent organic polymers (ICOPs) are of particular importance in CCU technologies because they not only have all the advantages of COPs but also possess charged cationic skeletons paired with counter-ions which provide additional CO<sub>2</sub> affinity owing to their electrostatic interactions with CO<sub>2</sub> molecules.<sup>35,39–42</sup> Consequently, the CO<sub>2</sub> uptake capacity of viologen linked ICOPs is found to be significantly higher compared to their neutral counterparts.<sup>34,43,44</sup> Moreover, unlike other porous materials, selective recognition of viologen linked ICOPs can be manipulated by simply controlling the redox state of viologen or the nature of the counter-ions for the desired application.<sup>39,41</sup>

In recent years, several cationic viologen linked ICOPs with good surface areas have been reported for CCU.<sup>34,39,43–49</sup> The general understanding of these studies is that the high CO<sub>2</sub> capture capacity of viologen linked ICOPs is credited mostly to tetrel bonding interactions between the counter anions and

CO<sub>2</sub>.<sup>50</sup> Commonly, nitrogen-based groups in CCU applications are preferred for their Lewis basic character to form non-covalent interactions with the electron-deficient central carbon (Lewis acid) of CO<sub>2</sub>. However, in the case of viologen, the quaternary nitrogen (N<sup>+</sup>) atom lacks lone electron pairs, and hence acts as a Lewis acid; consequently, the formation of efficient interactions between cation (N<sup>+</sup>) nitrogen and the electron-rich terminal oxygen atoms of CO<sub>2</sub>, commonly referred to as pnictogen bonds, is highly possible.<sup>19,51</sup> Yet, the pnictogen (O<sub>CO<sub>2</sub></sub> ··· N<sup>+</sup>) interaction is often disregarded, and its contribution to CO<sub>2</sub> capture has not been reported.

However, despite their attractive features for CCU applications, only a limited number of viologen linked ICOPs have been reported in the literature, mainly due to their low physicochemical stability. This drawback can be overcome by the incorporation of viologens into polymeric systems with suitable rigid and symmetric macrocycles such as porphyrin.<sup>52</sup> The incorporation of porphyrin brings three advantages. First, unstable cationic species get stabilized by extended delocalized polymeric structures. Second, porphyrin is another excellent N containing molecular building block, which can increase the CO<sub>2</sub> uptake and selectivity through the CO<sub>2</sub> interaction with pyrroles (–C=N, –NH). Third, the metalation of the porphyrin core with Lewis acid metals such as zinc(II) can promote additional non-covalent interactions with the electron-rich terminal oxygen atoms of CO<sub>2</sub>, known as spodium bonding.<sup>53</sup> In addition to their multiple CO<sub>2</sub>-philic functional sides, both viologen and porphyrin are also known to exhibit effective CO<sub>2</sub> catalytic conversion, which makes them very promising bifunctional materials in CCU applications.<sup>46–48,54–56</sup>

Herein, based on the above considerations, we report viologen-linked porphyrin ICOPs (**H2-ICOP** and **Zn-ICOP**) synthesized through the Zincke reaction of H2 and Zn(II) tetrakis(4-aminophenyl) porphyrin with viologen Zincke salt, as presented in Scheme 1.



Scheme 1 Schematic representation of the synthesis of the viologen-linked porphyrin ICOPs *via* a Zincke reaction under solvothermal conditions.



The resultant ICOPs were characterized with various experimental analyses including FTIR spectroscopy, solid-state  $^{13}\text{C}$  NMR spectroscopy, energy-dispersive X-ray spectroscopy (EDX), diffuse reflectance spectroscopy (DRS), thermogravimetric analysis (TGA), powder X-ray diffraction (PXRD), field emission scanning electron microscopy (SEM), transmission electron microscopy (TEM) and dynamic light scattering (DLS). Furthermore, their  $\text{CO}_2$  capture capacity,  $\text{CO}_2/\text{N}_2$  selectivity, and  $\text{CO}_2$  catalytic conversion performances were explored. Brunauer–Emmett–Teller (BET) surface area analyses reveal that both **H2-ICOP** ( $9\text{ m}^2\text{ g}^{-1}$ ) and **Zn-ICOP** ( $20\text{ m}^2\text{ g}^{-1}$ ) possess very low surface areas. Yet, despite their nearly non-porous surfaces, especially **H2-ICOP** exhibits a very large  $\text{CO}_2$  capture capacity ( $62.9\text{ mg g}^{-1}$ ) and  $\text{CO}_2/\text{N}_2$  selectivity, which indicates powerful non-covalent interactions with  $\text{CO}_2$ . Detailed theoretical analyses have been conducted to decode insights into these unexpected large  $\text{CO}_2$  capture capacities and  $\text{CO}_2/\text{N}_2$  selectivity. The strengths of possible non-covalent interactions, such as hydrogen, tetrel, pnictogen, and spodium bonding, between  $\text{CO}_2$  molecules and the **H2-ICOP** and **Zn-ICOP** surfaces were calculated, in terms of the contribution to the  $\text{CO}_2$  capture capacity. Additionally, the  $\text{CO}_2$  catalytic conversion performances of **Zn-ICOP** and **H2-ICOP** gave good yields of 83% and 54% in mild conditions, respectively.

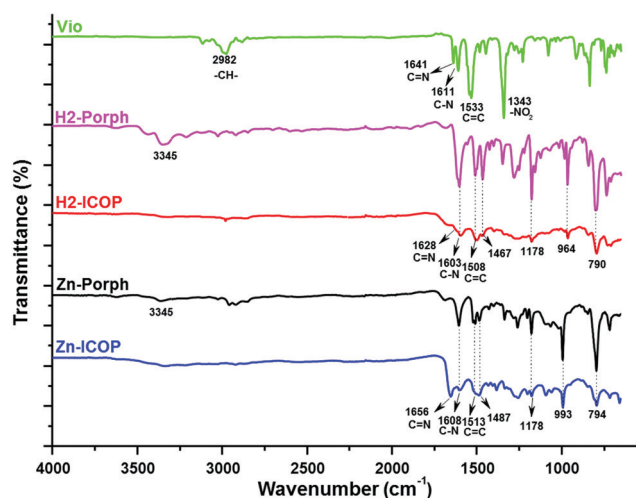


Fig. 1 FTIR spectra of **H2-ICOP** and **Zn-ICOP** in comparison with the corresponding monomers (**H2-Porph**, **Zn-Porph** and **Vio**).

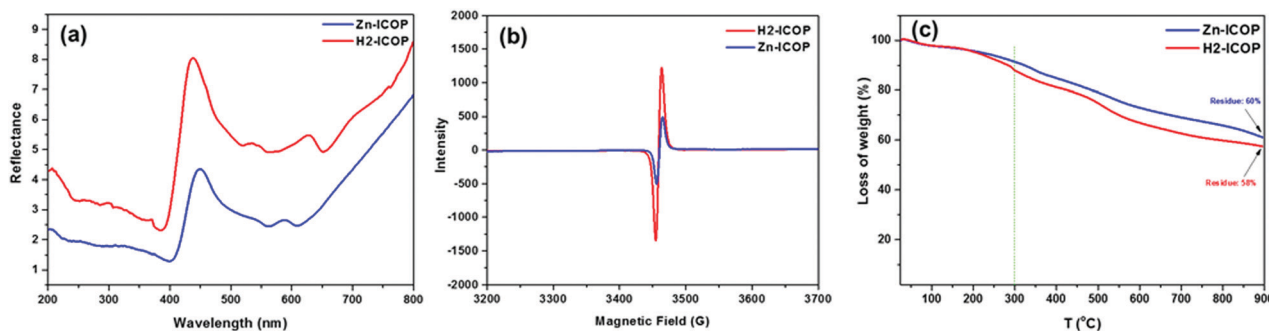


Fig. 2 DR spectra (a), EPR signals (b) and TGA curves (c) of **H2-ICOP** and **Zn-ICOP**.

## 2. Results and discussion

### 2.1. Synthesis and characterization

The synthesis of the ionic covalent organic polymers (**H2-ICOP** and **Zn-ICOP**) was carried out under solvothermal conditions by the Zincke reaction of 1,1'-bis(2,4-dinitrophenyl)-[4,4'-bipyridine]-1,1'-dium dichloride (**Vio**) with either 5,10,15,20-tetrakis(4-aminophenyl)porphyrin (**H2-Porph**) or 5,10,15,20-tetrakis(4-aminophenyl)porphyrinato zinc(II) (**Zn-Porph**) in a mixture of 1,4-dioxane : water (4 : 1, v/v) or DMF : water (4 : 1, v/v) (Scheme 1, for details see the ESI<sup>†</sup>). A gel-like material was obtained in the DMF : water mixture, whereas a powder was obtained in the 1,4-dioxane : water mixture (Fig. S1, ESI<sup>†</sup>). Washing the solids with the appropriate solvents is found to be crucial to remove unreacted starting materials and any smaller oligomers that may have formed. Therefore, the solids were washed with ethanol and DMSO several times until a colourless solution was obtained. The purification procedure was completed by washing with water and acetone. Complementary methods were used for the detailed structural characterization of the ICOPs. The formation of the ICOPs is confirmed by Fourier-transform infrared (FTIR) spectroscopy and solid-state  $^{13}\text{C}$  NMR. In FTIR (Fig. 1), the decline of the characteristic  $-\text{NH}_2$  peak at  $3345\text{ cm}^{-1}$  and  $-\text{NO}_2$  peak at  $1343\text{ cm}^{-1}$  and the appearance of the characteristic pyridinium  $\text{C}=\text{N}$  peak at  $1628\text{ cm}^{-1}$  for **H2-ICOP** and  $1656\text{ cm}^{-1}$  for **Zn-ICOP** indicate the loss of the 2,4-dinitroaniline group and the formation of viologen-linked ICOPs. Besides, the peaks belonging to the porphyrin ring at  $964$  and  $790\text{ cm}^{-1}$  for **H2-ICOP** and at  $993$  and  $794\text{ cm}^{-1}$  for **Zn-ICOP** confirm the formation of the expected materials. The same structures are obtained for **H2-ICOP-dx** and **Zn-ICOP-dx** with identical FTIR as shown in Fig. S2 (ESI<sup>†</sup>). The solid-state  $^{13}\text{C}$  NMR spectra (Fig. S3, ESI<sup>†</sup>) of the materials show broad multi-peaks between  $\delta = 100$  and  $170$  ppm. The peaks at  $151$  ppm for **H2-ICOP** and  $152$  ppm for **Zn-ICOP** can be attributed to the carbon signals in the bipyridinium moieties, whereas the peaks at  $122$  ppm for **H2-ICOP** and **Zn-ICOP** correspond to phenyl carbons of the porphyrin subunit.

The diffuse reflectance spectroscopy (DRS) of **H2-ICOP** and **Zn-ICOP** displays the characteristic Soret and Q bands of the porphyrin at  $436\text{ nm}$  and  $535\text{ nm}$  for **H2-ICOP**, and  $447\text{ nm}$  and  $538\text{ nm}$  for **Zn-ICOP** (Fig. 2a). Moreover, characteristics of viologen radical bands were observed at  $627\text{ nm}$  for **H2-ICOP**



and 586 nm for **Zn-ICOP**. **H2-ICOP** and **Zn-ICOP** exhibit an electron paramagnetic resonance (EPR) signal (Fig. 2b). The radical character of these ICOPs is the result of charge transfer from the aromatic porphyrin core to the viologen unit and is an indication of the highly conjugated structures.<sup>57</sup>

Thermogravimetric analysis (TGA) shows that **H2-ICOP** and **Zn-ICOP** exhibit thermal stability up to 300 °C with slight weight losses (Fig. 2c). However, it is noteworthy that both materials retain about 60% of their initial mass even at 900 °C, indicating good thermal stability. **H2-ICOP** and **Zn-ICOP** have similar experimental PXRD profiles with low angle diffraction peaks in the vicinity of  $2\theta$  values of  $5^\circ$ , which is characteristic for expected large unit-cell parameters (Fig. S4, ESI<sup>†</sup>). However, the broadening of peaks in both profiles in combination with a large peak at *ca.*  $22.5^\circ$  indicates a semi-crystalline nature of the studied materials. To determine the structures of **H2-ICOP** and **Zn-ICOP**, the geometry optimization of constructed models having the eclipsed (AA) and staggered (AB) topology was performed using the ABINIT code using the following unit cell parameters:  $a = b = 35.563$ ,  $c = 4.09$  (7.8 for the staggered structure) Å,  $\alpha = \beta = \gamma = 90^\circ$ , space group *P1*. The comparisons of both the experimental and calculated PXRD profiles based on the relaxed models are presented in Fig. S4a for **H2-ICOP** and in Fig. S4b (ESI<sup>†</sup>) for **Zn-ICOP**. The experimental PXRD profiles of both ICOPs are in good agreement with the simulated staggered AB-stacking model (Fig. S4d, ESI<sup>†</sup>). Since the PXRD patterns of **H2-ICOP-dx** and **Zn-ICOP-dx** showed an amorphous nature rather than a semi-crystalline structure, **H2-ICOP** and **Zn-ICOP** were used for further investigations. Elemental mapping by energy dispersive spectroscopy (EDS) exhibits the elements C, N, and Cl for **H2-ICOP** and C, N, Cl, and Zn for **Zn-ICOP** (Fig. S5, ESI<sup>†</sup>), which is consistent with the compositions of our ICOPs. Dynamic light scattering (DLS) analyses showed two particle populations with an average colloidal particle size in the range between 1 and 10  $\mu\text{m}$  for both ICOPs, suggesting a polydisperse nature (Fig. S6, ESI<sup>†</sup>). The stability of colloidal systems of **H2-ICOP**

and **Zn-ICOP** was evaluated with zeta potential measurements in water (pH = 7.4) (Fig. S7, ESI<sup>†</sup>). Interestingly, the zeta potential of **H2-ICOP** shows a positive value (+25), whereas **Zn-ICOP** shows a negative zeta potential value (−21.6). These high absolute values of the zeta potential of **H2-ICOP** and **Zn-ICOP** indicate a stable state of their colloidal systems, which is also confirmed by observation of the Tyndall effect (Fig. S8, ESI<sup>†</sup>). Furthermore, the zeta potential data not only reflect the stability of the colloidal systems of **H2-ICOP** and **Zn-ICOP** dispersions in water but also can be used to explain the adsorption and conversion mechanisms of  $\text{CO}_2$ , which we will discuss in related sections.

Depending on the solvent mixture used, structures with different morphologies were obtained. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) studies reveal that the ICOPs obtained by using the DMF : water mixture (**H2-ICOP** and **Zn-ICOP**) exhibit a sheet-like morphology, whereas the ICOPs obtained by using the 1,4-dioxane : water mixture (**H2-ICOP-dx** and **Zn-ICOP-dx**) exhibit a spherical morphology (Fig. 3). Uniform spheres with an average diameter of 1.4  $\mu\text{m}$  for **H2-ICOP-dx** and 0.65  $\mu\text{m}$  for **Zn-ICOP-dx** were observed by both SEM (Fig. 3b and d and Fig. S9, ESI<sup>†</sup>) and TEM analysis (Fig. 3f and h).

## 2.2. $\text{CO}_2$ uptake and $\text{CO}_2/\text{N}_2$ selectivity performance

To investigate the permanent porosity of **H2-ICOP** and **Zn-ICOP**, krypton (Kr) adsorption–desorption isotherms were measured *via* the Brunauer–Emmett–Teller (BET) model, at 77 K (for details see the ESI<sup>†</sup>). As shown in Fig. 4b, both **H2-ICOP** and **Zn-ICOP** show typical type-II reversible adsorption isotherms and their porosities are found to be mesoporous in the range of 3–20 nm, whereas the nitrogen ( $\text{N}_2$ ) adsorption–desorption isotherms show non-porous surfaces. The specific surface areas of **H2-ICOP** and **Zn-ICOP** were found to be  $9 \text{ m}^2 \text{ g}^{-1}$  and  $20 \text{ m}^2 \text{ g}^{-1}$ , respectively (Fig. 4a). This difference in the BET surface areas can be explained by the zeta potential values of **H2-ICOP** (+25) and **Zn-ICOP** (−21.6) (Fig. S7, ESI<sup>†</sup>). The positive

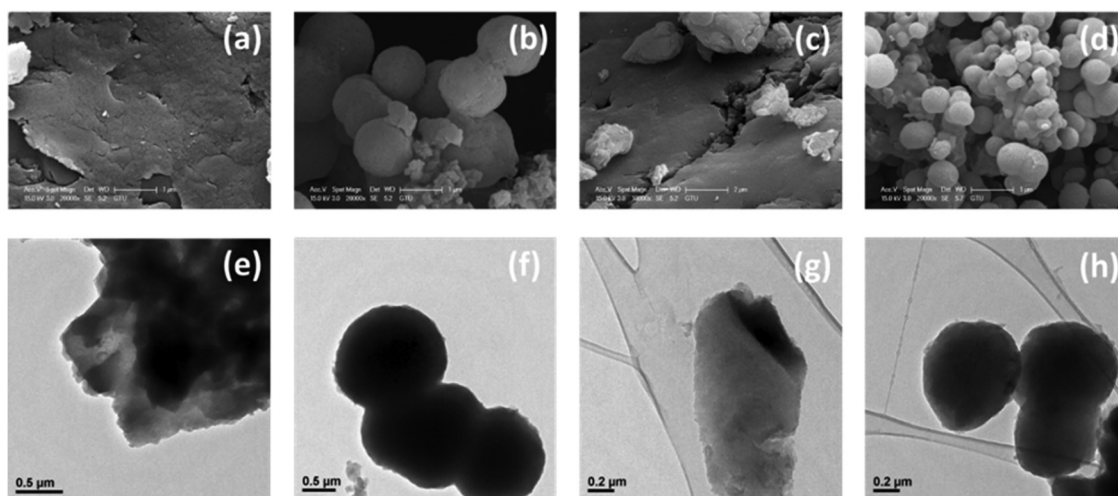


Fig. 3 Microscopic characterization [SEM (top row) and TEM (bottom row)] of **H2-ICOP** (a and e) and **Zn-ICOP** (c and g) prepared in DMF : water (4 : 1, v/v) and obtained as plates; and **H2-ICOP-dx** (b and f) and **Zn-ICOP-dx** (d and h) prepared in 1,4-dioxane : water (4 : 1, v/v) and obtained as spheres.



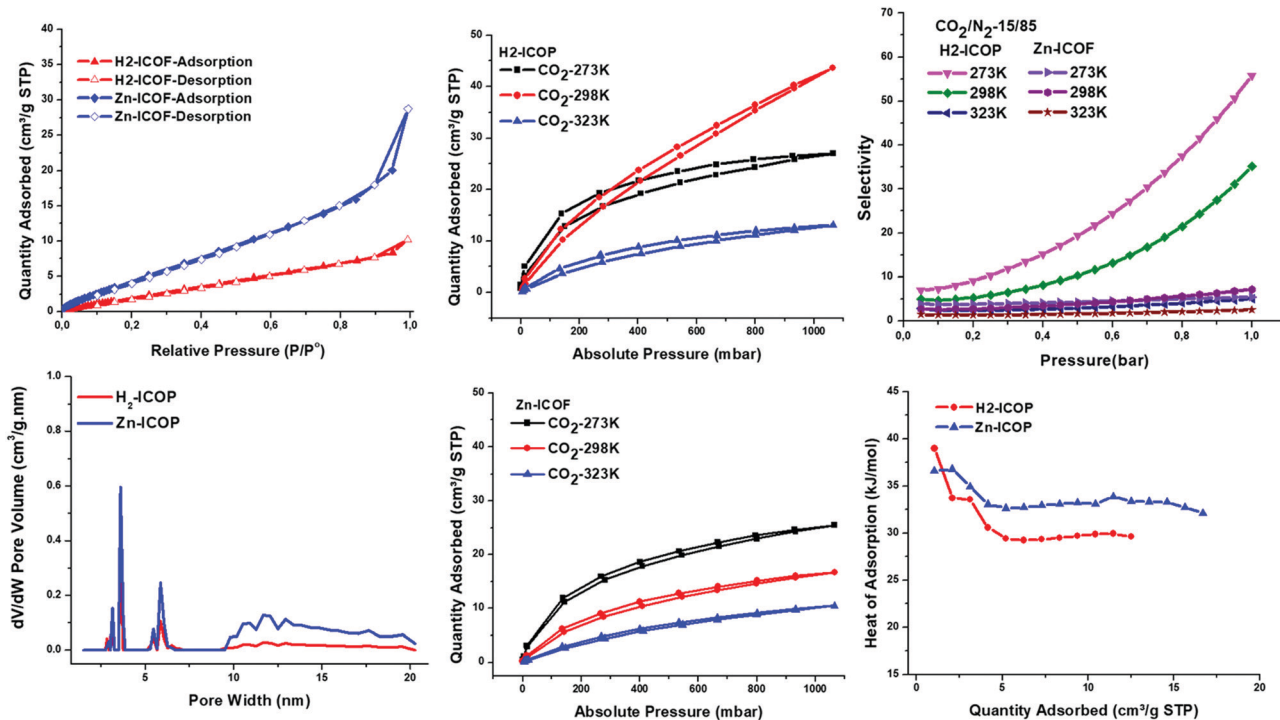


Fig. 4 (a) Kr adsorption/desorption isotherms of **H2-ICOP** and **Zn-ICOP** measured at 77 K, filled and empty symbols represent adsorption and desorption, respectively. (b) Pore size distribution of **H2-ICOP** and **Zn-ICOP** calculated from Kr isotherms calculated using NLDFT.  $\text{CO}_2$  adsorption isotherms of **H2-ICOP** (c) and **Zn-ICOP** (d) collected up to 1 bar at 273, 298, and 323 K. (e)  $\text{CO}_2/\text{N}_2$  (IAST method) selectivity of **H2-ICOP** and **Zn-ICOP** at 273 K, 298 K, and 323 K. (f) The isothermic heat of adsorption ( $Q_{st}$ ) plots of  $\text{CO}_2$  for **H2-ICOP** and **Zn-ICOP**.

zeta potential value suggests that the pores are occupied by nearly all of the chloride counter ions and they do not remain on the surface of **H2-ICOP**, whereas the negative zeta potential value indicates that some chloride counter-ions remain on the surface of **Zn-ICOP**. Notably, the surface areas of both ICOPs are one of the lowest values reported to date for any ICOP. These relatively low values are likely due to the pores of the materials being occupied by chloride counterions and their semi-crystalline state and staggered morphology with an AB stacking sequence (Fig. S4d, ESI†).

Owing to their multiple  $\text{CO}_2$ -philic sides, despite their low surface areas, we explored the affinity of **H2-ICOP** and **Zn-ICOP** toward  $\text{CO}_2$  and  $\text{N}_2$ . To evaluate their performance for  $\text{CO}_2$  capture, we carried out temperature-dependent  $\text{CO}_2$  uptake

measurements at 273, 298, and 323 K up to 1 bar (Fig. 4c and d). The  $\text{CO}_2$  capture capacity of **H2-ICOP**, despite the lower BET surface area, is found to be up to 26 ( $42.4 \text{ mg g}^{-1}$ , 273 K), 44 ( $62.9 \text{ mg g}^{-1}$ , 298 K), and  $13 \text{ cm}^3 \text{ g}^{-1}$  ( $17.3 \text{ mg g}^{-1}$ , 323 K) at 1 bar, which is much higher than that of **Zn-ICOP**, 25 ( $39.3 \text{ mg g}^{-1}$ , 273 K), 16.7 ( $24 \text{ mg g}^{-1}$ , 298 K) and  $10.2 \text{ cm}^3 \text{ g}^{-1}$  ( $13.9 \text{ mg g}^{-1}$ , 323 K) at 1 bar, respectively. Notably, the  $\text{CO}_2$  uptake capacities are not saturated for **H2-ICOP** within the pressure range, suggesting that the  $\text{CO}_2$  uptake capacities can be further improved with increased pressure. Remarkably, the  $\text{CO}_2$  capture capacities of **H2-ICOP** and **Zn-ICOP** are one of the highest values reported among previously reported viologen based ICOPs and ICOPs with much larger surface areas (Table 1). The  $\text{CO}_2$  capture capacity of these viologen linked

Table 1 BET surface area,  $\text{CO}_2$  uptake, selectivity, and heat adsorptions ( $Q_{st}$ ) of the ICOPs

ICOP	BET surface area ( $\text{m}^2 \text{ g}^{-1}$ )	$\text{CO}_2$ adsorption ( $\text{mg g}^{-1}$ )			$\text{CO}_2/\text{N}_2$ selectivity (15/85) (IAST) 1 bar		$Q_{st}$ ( $\text{kJ mol}^{-1}$ )	Pressure (bar)	Ref.
		273 K	298 K	323 K	273 K	298 K			
<b>H2-ICOP</b>	9	42.4	62.9	17.3	56.5	35	39	1	This work
<b>Zn-ICOP</b>	20	39.3	24	13.9	5.6	6.9	36	1	This work
PCP-Cl	755	101	61.4	—	34	—	28.5	1	39
V-PCIF-Cl	174	86.7	62.4	—	—	—	56.6	1	43
POV-V1	812	—	40.5	—	—	—	25	1.1	49
POV-V2	960	—	55.9	—	—	—	24	1.1	49
c-CTF-400	744	126	83	52	—	—	49	1	34
c-CTF-450	861	99	62	38	—	—	46	1	34
c-CTF-500	1247	133	80	47	—	—	43	1	34
SYSU-Zn@IL1	38	68	40	—	—	—	27.2	1	47



ICOFs and ICOPs is attributed mainly to tetrel bonding interactions between the counter anions and CO<sub>2</sub>. However, as the positive zeta potential value of **H2-ICOP** shows that the pores are occupied by nearly all of the chloride counter ions and they do not remain on the surface, yet **H2-ICOP** has a very high CO<sub>2</sub> capture capacity, the results indicate that **H2-ICOP**, due to our molecular design, possesses much stronger non-covalent interactions with CO<sub>2</sub> than the counter anions.

To gain further insights from the non-covalent interactions between the materials and CO<sub>2</sub> molecules, the CO<sub>2</sub> isosteric heat of adsorption ( $Q_{st}$ ) of **H2-ICOP** and **Zn-ICOP** was obtained with the Clausius–Clapeyron equation from the CO<sub>2</sub> uptake isotherms recorded (Fig. 4f). The  $Q_{st}$  values for CO<sub>2</sub> were found to be 39 and 36 kJ mol<sup>-1</sup> for **H2-ICOP** and **Zn-ICOP**, respectively, at zero coverage. This difference of the  $Q_{st}$  value for the two polymers shows that the non-covalent interactions of the CO<sub>2</sub> molecules with the skeleton of **H2-ICOP** are more efficient than with **Zn-ICOP**, which may explain the higher CO<sub>2</sub> capture capacity of **H2-ICOP** compared to **Zn-ICOP**. It is also worth mentioning that the  $Q_{st}$  values of the polymers are moderate, not exceeding 50 kJ mol<sup>-1</sup>, which implies that CO<sub>2</sub> is physically adsorbed by both ICOPs and the recyclability of the adsorbent at a low energy penalty.

Additionally, to assess the potential in separation of CO<sub>2</sub> from flue gas (> 70% N<sub>2</sub>), the adsorption selectivity of CO<sub>2</sub> over N<sub>2</sub> (15/85) of **H2-ICOP** and **Zn-ICOP** was calculated with Myers and Prausnitz's ideal adsorbed solution theory (IAST) at three different temperatures (273, 298, and 320 K) up to 1 bar (Fig. 4e and Table 1).<sup>58</sup> The selectivity of CO<sub>2</sub> from CO<sub>2</sub>/N<sub>2</sub> (15/85) of **H2-ICOP** and **Zn-ICOP** is 55.7 and 5.5 at 273 K, 35.1 and 7.2 at 298 K, and 5.1 and 2.55 at 323 K, respectively. As expected, **H2-ICOP** exhibits much higher selectivity compared to **Zn-ICOP**, which also indicates powerful CO<sub>2</sub> affinity of **H2-ICOP**.

### 2.3. Computational analysis of non-covalent bonds

The high CO<sub>2</sub> capture and selectivity capacities of **H2-ICOP** and **Zn-ICOP**, despite their low surface areas, clearly show the powerful non-covalent interactions between CO<sub>2</sub> molecules and multiple CO<sub>2</sub>-philic moieties of **H2-ICOP** and **Zn-ICOP**. Theoretical analyses (for details of the computational methodology see the ESI†) have been performed to get insights into the possible non-covalent interactions between CO<sub>2</sub> molecules and the surfaces of **H2-ICOP** and **Zn-ICOP**, and their contribution to the selective CO<sub>2</sub> uptake of these compounds.

To model the mentioned non-covalent interactions, the fragments **H2-ICOP** and **Zn-ICOP** were 'cut off' from the polymeric chains and the linkers were replaced by hydrogen atoms. **H2-ICOP** and **Zn-ICOP** contain two porphyrin cores, a chlorine counterion, and a positively charged viologen linker. The  $\sigma$ -hole formation on the surface of **H2-ICOP**, **Zn-ICOP**, and CO<sub>2</sub> has been visualized using electrostatic potential maps (MEP) and the results are displayed in Fig. 5 along with the corresponding electrostatic potential values. The calculated MEP surfaces show that a maximum of positive potential ( $\sigma$ -hole) involves a region with the cationic viologen subunits and **Zn-ICOP** porphyrin core (Zn) as well as the carbon atom C<sub>CO<sub>2</sub></sub>, which shows the Lewis acid

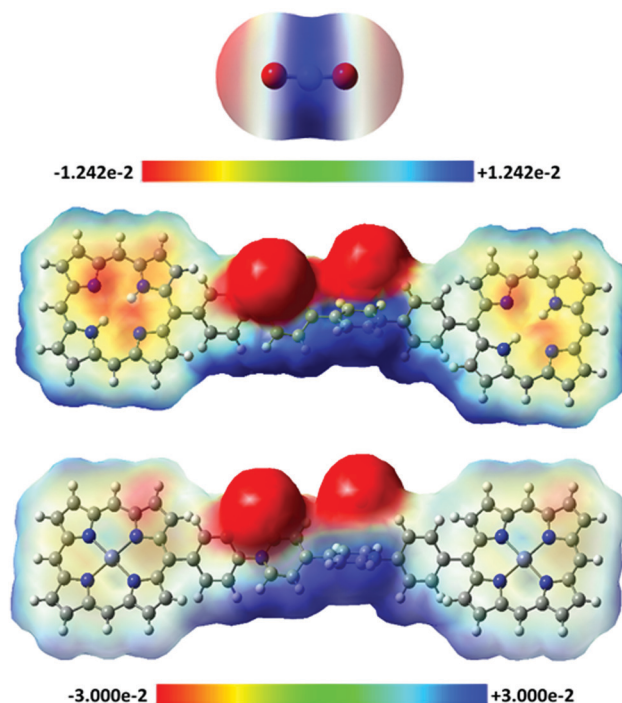


Fig. 5 Electrostatic potentials mapped on the molecular surfaces of CO<sub>2</sub>, **H2-ICOP** and **Zn-ICOP**. The values of the MEPs lie in the intervals  $-7.794$ ,  $+7.794$  kcal mol<sup>-1</sup> for CO<sub>2</sub> and  $-18.825$ ,  $+18.825$  kcal mol<sup>-1</sup> for **H2-ICOP** and **Zn-ICOP**.

character of these regions. The negative electrostatic potential is located in the vicinity of oxygen O<sub>CO<sub>2</sub></sub>, chlorine atoms, and nitrogen atoms in the **H2-ICOP** porphyrin core (Fig. 6). Thus, the positive and negative MEP distributions of **H2-ICOP**, **Zn-ICOP**, and CO<sub>2</sub> indicate that attractive interactions are favourable for the formation of the above mentioned non-covalent bonds.

The MEP analyses have revealed possible non-covalent interactions, such as hydrogen, tetrel, pnictogen, and spodium bonds formed between CO<sub>2</sub> molecules and the surfaces of **H2-ICOP** and **Zn-ICOP**, and their contribution to the selective CO<sub>2</sub> uptake of these compounds (Fig. 6).

These noncovalent interactions can be uniformly defined based on the positive electrostatic region present on an atom due to the anisotropic distribution of the electron density. A positive electrostatic region present on an atom along a  $\sigma$ -polymer is called a  $\sigma$ -hole. The size and magnitude of a  $\sigma$ -hole are dependent on both the nature of its atom and the electron-withdrawing ability of groups

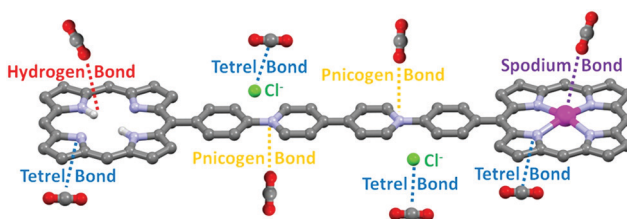


Fig. 6 Scheme of possible non-covalent interactions between CO<sub>2</sub> and **H2-ICOP** and **Zn-ICOP**.



attached to this atom. These  $\sigma$ -holes can have an attractive interaction with electron donors such as Lewis bases, anions or radicals. Depending on the  $\sigma$ -hole origins, these interactions are called tetrel bonding (group IV), pnictogen bonding (group V), chalcogen bonding (group VI), halogen bonding (group VII) or spodium bonding (group XII).<sup>59</sup>

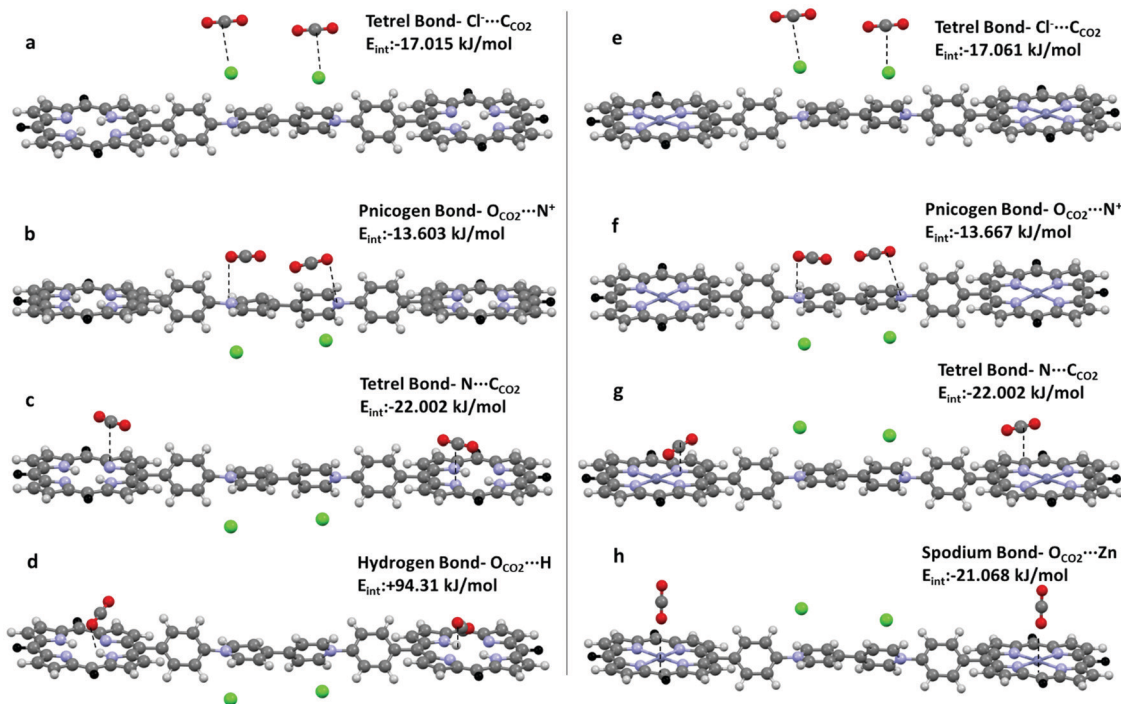
Symmetry adapted perturbation theory (SAPT) analysis, which partitions the attractive forces into electrostatic ( $E_{\text{elst}}$ ), exchange-repulsion ( $E_{\text{exch}}$ ), induction ( $E_{\text{ind}}$ ), and dispersion ( $E_{\text{disp}}$ ) terms, has been carried out to calculate the interaction energy of hydrogen ( $\text{O}_{\text{CO}_2} \cdots \text{H}$ ), tetrel ( $\text{C}_{\text{CO}_2} \cdots \text{N}$ ,  $\text{C}_{\text{CO}_2} \cdots \text{Cl}^-$ ), pnictogen ( $\text{O}_{\text{CO}_2} \cdots \text{N}^+$ ), and spodium bonds ( $\text{O}_{\text{CO}_2} \cdots \text{Zn}$ ) in **H2-ICOP** and **Zn-ICOP** and estimate the preferable binding sites to capture  $\text{CO}_2$  molecules on their surfaces (Table 3). For all studied non-covalent interactions, the calculated attractive components  $E_{\text{elst}}$ ,  $E_{\text{ind}}$ , and  $E_{\text{disp}}$  provide sufficient stabilization to overcome the repulsive exchange component  $E_{\text{exch}}$ , and the

resultant interaction energy ( $E_{\text{int}}$ ) values are negative, except hydrogen bonding. The value of  $E_{\text{exch}}$  for hydrogen bonds in **H2-ICOP** is very large and suppresses the other attractive components, and therefore the resulting interaction energy is positive, which indicates that the formation of H-bonds between  $\text{CO}_2$  and  $-\text{NH}$  (porp) is not favourable (Table 2 and Fig. 7d). Dispersion forces ( $E_{\text{disp}}$ ) are found to be dominant in the attractive binding energies of pnictogen ( $\text{O}_{\text{CO}_2} \cdots \text{N}^+$ ) and  $\text{C}_{\text{CO}_2} \cdots \text{N}$  tetrel bonds and spodium bonds ( $\text{O}_{\text{CO}_2} \cdots \text{Zn}$ ), while electrostatic interactions ( $E_{\text{elst}}$ ) dominate in  $\text{C}_{\text{CO}_2} \cdots \text{Cl}^-$  tetrel bonds in both compounds. The percentage contribution of the dispersion term in the overall attractive forces for pnictogen bonds consists of 73% in **CO<sub>2</sub>-H2-ICOP** and **CO<sub>2</sub>-Zn-ICOP**, while for  $\text{C}_{\text{CO}_2} \cdots \text{N}$  tetrel bonds in these systems it is equal to 58% and 66%, respectively. For spodium bonds the dispersion term constitutes 53%. For  $\text{C}_{\text{CO}_2} \cdots \text{Cl}^-$  tetrel bonds in both compounds the percentage contribution of electrostatic interactions in the overall attractive forces consists of 58%.

**Table 2** Summary of the SAPT results ( $\text{kJ mol}^{-1}$ ) for pnictogen ( $\text{O}_{\text{CO}_2} \cdots \text{N}^+$ ), tetrel ( $\text{C}_{\text{CO}_2} \cdots \text{N}$ ,  $\text{C}_{\text{CO}_2} \cdots \text{Cl}^-$ ), hydrogen ( $\text{H} \cdots \text{O}_{\text{CO}_2}$ ) and spodium ( $\text{Zn} \cdots \text{O}_{\text{CO}_2}$ ) bonds in **CO<sub>2</sub>-H2-ICOP** and **CO<sub>2</sub>-Zn-ICOP**.  $R$  is the bond length ( $\text{\AA}$ )

Compound	LB $\cdots$ LA	Bond type	$R$	$E_{\text{elst}}$	$E_{\text{exch}}$	$E_{\text{ind}}$	$E_{\text{disp}}$	$E_{\text{int}}$
<b>H2-ICOP</b>	$\text{O}_{\text{CO}_2} \cdots \text{N}^+$	Pnictogen	3.115	-6.1	16.8	-2.0	-22.2	-13.6
	$\text{Cl}^- \cdots \text{C}_{\text{CO}_2}$	Tetrel	3.42	-16.3	11.0	-3.8	-7.9	-17.0
	$\text{N} \cdots \text{C}_{\text{CO}_2}$	Tetrel	2.976	-21.7	42.3	-5.5	-37.1	-22.0
	$\text{O}_{\text{CO}_2} \cdots \text{H}$	Hydrogen	1.961	-177.6	398.9	-21.2	-105.9	+94.3
<b>Zn-ICOP</b>	$\text{O}_{\text{CO}_2} \cdots \text{N}^+$	Pnictogen	3.115	-6.2	16.8	-2.0	-22.3	-13.7
	$\text{Cl}^- \cdots \text{C}_{\text{CO}_2}$	Tetrel	3.42	-16.4	11.0	-3.8	-7.9	-17.1
	$\text{N} \cdots \text{C}_{\text{CO}_2}$	Tetrel	2.976	-14.2	42.7	-5.2	-38.4	-15.2
	$\text{O}_{\text{CO}_2} \cdots \text{Zn}$	Spodium	2.6	-19.8	30.2	-5.8	-28.8	-21.1

<sup>a</sup> The D-H  $\cdots$  A angles for both  $\text{CO}_2$  are 125.8 and 118.7°.



**Fig. 7** Formation of (a, e, c and g) tetrel, (b and f) pnictogen, (d) hydrogen and (h) spodium bonds in **H2-ICOP** and **Zn-ICOP**.



The strength of the non-covalent interactions in **CO<sub>2</sub>-H2-ICOP** and **CO<sub>2</sub>-Zn-ICOP** is decreasing in the following order  $\Delta E_{C\cdots N} > \Delta E_{C\cdots Cl^-} > \Delta E_{O\cdots N^+}$  and  $\Delta E_{Zn\cdots O} > \Delta E_{C\cdots Cl^-} > \Delta E_{C\cdots N} > \Delta E_{O\cdots N^+}$ , respectively (Table 2 and Fig. 7a-h). The binding energy of  $C_{CO_2}\cdots N$  tetrel bonds in **CO<sub>2</sub>-H2-ICOP** is  $-22.02$  kJ mol<sup>-1</sup> and is the strongest among the studied non-covalent interactions. Interestingly, upon Zn metalation in the porphyrin core, the binding energy of  $C_{CO_2}\cdots N$  tetrel bonds in **CO<sub>2</sub>-Zn-ICOP** is decreased to  $-15.163$  kJ mol<sup>-1</sup>, probably due to an increase of the positive electrostatic potential around nitrogen atoms (Fig. 6) in the porphyrin core, which resulted in the formation of weaker tetrel bonds ( $C_{CO_2}\cdots N$ ) with  $CO_2$ . In addition, further analyses were performed to calculate the binding energy of the simultaneous presence, on the same porphyrin core, of two  $C_{CO_2}\cdots N$  tetrel bonds in **H2-ICOP** and spodium and  $C_{CO_2}\cdots N$  tetrel bonds in **Zn-ICOP**. The analyses reveal that the simultaneous presence of spodium and  $C_{CO_2}\cdots N$  tetrel bonds is impossible on the same porphyrin core in **Zn-ICOP** because of the strong repulsion between two  $CO_2$  molecules (Table S1 and Fig. S10, ESI<sup>†</sup>), while two tetrel bonds may form in the **H2-ICOP** porphyrin core because of negligible repulsion between  $CO_2$  molecules (Fig. S11 and Table S1, ESI<sup>†</sup>). Overall, in our fragment model, **H2-ICOP** can potentially form two pnictogen, two  $C_{CO_2}\cdots Cl^-$  and four  $C_{CO_2}\cdots N$  tetrel bonds with  $CO_2$ , while **Zn-ICOP** can form two pnictogen, two  $C_{CO_2}\cdots Cl^-$  tetrel, and two spodium bonds with  $CO_2$ . The major  $CO_2$  uptake contribution comes from the four  $C_{CO_2}\cdots N$  tetrel bonding interactions for **H2-ICOP**, whereas the two spodium bonding interactions for **Zn-ICOP**. In conclusion, **H2-ICOP** has more binding sites with more powerful non-covalent interactions that lead to an enhancement of the  $CO_2$  uptake compared to **Zn-ICOP**, which is in good agreement with the experimental results.

#### 2.4. The catalytic performance in $CO_2$ conversion into cyclic carbonates

To evaluate the catalytic activities of viologen-linked porphyrin **H2-ICOP** and **Zn-ICOP**, the cycloaddition of  $CO_2$  to propylene oxide was chosen as a model reaction and the results are listed in Table 3. The reactions were conducted under 1.0 MPa  $CO_2$  pressure and solvent and co-catalyst free conditions at 80 °C (for details see the ESI<sup>†</sup>).

The compared catalysts **Zn-ICOP** and **H2-ICOP** gave yields of 83% and 54%, respectively. Surprisingly, **Zn-ICOP**, despite having a significantly lower  $CO_2$  uptake capacity, displayed better catalytic activity than **H2-ICOP**. The high activity of **Zn-ICOP** can be attributed to the synergistic effect of Lewis acid Zn sites and a nucleophile counter anion ( $Cl^-$ ). The zeta potential data revealed that **Zn-ICOP** possesses a counter anion ( $Cl^-$ ) on its surface, whereas **H2-ICOP** does not, which indicates the crucial role of the counter anion ( $Cl^-$ ) in the mechanism of this catalytic reaction.<sup>46,47</sup> Notably, the catalytic activity of **Zn-ICOP** was achieved with lowered temperature and  $CO_2$  pressure, in a solvent-free reaction system, and was comparable to that of most of the reported examples (Table 3).









The catalytic performance of **Zn-ICOP** was compared with that of the corresponding polymer **SYSU-Zn@IL1**( $Br^-$ ) since

Table 3 The cycloaddition of  $CO_2$  with propylene oxide (PO) catalysed by various ICOPs

Catalyst	Loading	<i>T</i> (°C)	<i>P</i> <sub>CO<sub>2</sub></sub> (bar)	<i>t</i> (h)	Yield (%)	Ref.
<b>CTF-P-HSA</b>	0.1 g	130	6.9	4	83	60
<b>cCTF</b>	4 wt%	90	10	12	99	34
<b>PCP-Cl</b>	5 wt%	100	30	12	99	39
<b>Zn-ClF2-C<sub>2</sub>H<sub>5</sub></b>	0.18 mol%	120	25	5	98	61
<b>TBB-Bpy-a</b>	0.08 g	120	10	4	99	48
<b>COF-salen-Zn</b>	0.1 mol%	100	20	3	90	62
<b>SYSU-Zn@IL1</b>	0.16 mol%	80	10	12	62	47
<b>H2-ICOP</b>	0.16 mol%	80	10	12	54	<sup>a</sup>
<b>Zn-ICOP</b>	0.16 mol%	80	10	12	83	<sup>a</sup>

<sup>a</sup> This work (yields are determined by <sup>1</sup>H NMR).

Table 4 The addition of  $CO_2$  to various epoxides by the **Zn-ICOP** catalyst. Reaction conditions: epoxide (1 mL), catalyst (0.16 mol%), 80 °C, 1 MPa, 12 h

Epoxide				
Product				
Conversion (%)	83	42	77	4

both structures are based on Zn-porphyrin and viologen. **SYSU-Zn@IL1**, with a BET surface area of 38 m<sup>2</sup> g<sup>-1</sup>, has a nearly identical chemical composition to **Zn-ICOP**. Under similar conditions, **Zn-ICOP** had 83% conversion of PO, whereas **SYSU-Zn@IL1**( $Br^-$ ) could only afford a PO conversion of 62%. The higher activity of **Zn-ICOPz**( $Cl^-$ ) is mainly attributed to the higher nucleophilicity of its counter anions ( $Cl^- > Br^-$ ).

Under the optimized reaction conditions, the catalytic activity of **Zn-ICOP** was further studied over a variety of epoxides. As shown in Table 4, various epoxides are efficiently converted into the desired products with moderate yields under mild conditions by **Zn-ICOP**. With the increase of the size of epoxides, a steady decrease in the yield of cyclic carbonates was observed from PO (83%) and 1,2-epoxybutane (42%) to styrene oxide (4%), likely owing to their increasing steric hindrance, except for epichlorohydrin (77%) (Table 4). The deviation of epichlorohydrin's yield from the trend, despite its larger size, is probably due to additional non-covalent interactions between the chlorine functional group and  $CO_2$ .

### 3. Conclusion

Two viologen-porphyrin based ionic covalent organic polymers were constructed by a one-pot facile Zincke reaction. The BET surface area analyses reveal that both **H2-ICOP** (9 m<sup>2</sup> g<sup>-1</sup>) and **Zn-ICOP** (20 m<sup>2</sup> g<sup>-1</sup>) possess a very low surface area. Yet, despite their nearly non-porous surfaces, especially **H2-ICOP**



exhibits a very large CO<sub>2</sub> capture capacity and CO<sub>2</sub>/N<sub>2</sub> selectivity, which indicates efficient non-covalent interactions with CO<sub>2</sub>. The theoretical analyses show that **H2-ICOP** can potentially form two pnictogen, two C<sub>CO<sub>2</sub></sub>···Cl<sup>-</sup> and four C<sub>CO<sub>2</sub></sub>···N tetrel bonds with CO<sub>2</sub>, while **Zn-ICOP** can form two pnictogen, two C<sub>CO<sub>2</sub></sub>···Cl<sup>-</sup> tetrel, and two spodium bonds with CO<sub>2</sub>. The strength of the non-covalent interactions in **H2-ICOP** and **Zn-ICOP** is decreasing in the following order  $\Delta E_{C\cdots N} > \Delta E_{C\cdots Cl^-} > \Delta E_{O\cdots N^+}$  and  $\Delta E_{Zn\cdots O} > \Delta E_{C\cdots Cl^-} > \Delta E_{C\cdots N} > \Delta E_{O\cdots N^+}$ , respectively. The binding energy of C<sub>CO<sub>2</sub></sub>···N tetrel bonds in **CO<sub>2</sub>-H2-ICOP** is -22.02 kJ mol<sup>-1</sup> and is the strongest among the studied non-covalent interactions. The major CO<sub>2</sub> uptake contribution comes from the four C<sub>CO<sub>2</sub></sub>···N tetrel bonding interactions for **H2-ICOP**, whereas the two spodium bonding interaction for **Zn-ICOP**. Furthermore, the CO<sub>2</sub> catalytic conversion performances of **Zn-ICOP** and **H2-ICOP** gave encouraging yields of 83% and 54%, respectively. Surprisingly, **Zn-ICOP**, even with a significantly lower CO<sub>2</sub> uptake capacity, displayed better catalytic activity than **H2-ICOP**, probably due to the crucial role of the counter anion (Cl<sup>-</sup>) in the mechanism of this catalytic reaction.

Overall, we have demonstrated here that ICOPs with multiple CO<sub>2</sub>-philic sites can indeed exhibit very large CO<sub>2</sub> capture capacity, CO<sub>2</sub>/N<sub>2</sub> selectivity, and highly efficient catalytic activity of CO<sub>2</sub> cycloaddition of epoxides, owing to efficient non-covalent interactions with CO<sub>2</sub>, in spite of low surface areas. These results set a useful example for the importance of non-covalent interactions with CO<sub>2</sub> for the capture and conversion of CO<sub>2</sub> into value-added products. Therefore, we believe that these findings will prove to be of key importance to the design of bifunctional charged materials for CCU applications.

## Author contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

The authors thank the TUBITAK ULAKBIM High Performance and Grid Computing Center (TRUBA resources), Turkey, for computational facilities. Y. Zorlu acknowledges financial support from The Science Academy, Young Scientist Award (BAGEP).

## References

- 1 V. Scott, S. Gilfillan, N. Markusson, H. Chalmers and R. S. Haszeldine, *Nat. Clim. Change*, 2013, **3**, 105–111.
- 2 R. M. Cuéllar-Franca and A. Azapagic, *J. CO<sub>2</sub> Util.*, 2015, **9**, 82–102.
- 3 A. Modak, P. Bhanja, S. Dutta, B. Chowdhury and A. Bhaumik, *Green Chem.*, 2020, **22**, 4002–4033.
- 4 C. Hepburn, E. Adlen, J. Beddington, E. A. Carter, S. Fuss, N. Mac Dowell, J. C. Minx, P. Smith and C. K. Williams, *Nature*, 2019, **575**, 87–97.
- 5 G. Singh, J. Lee, A. Karakoti, R. Bahadur, J. Yi, D. Zhao, K. Albahily and A. Vinu, *Chem. Soc. Rev.*, 2020, **49**, 4360–4404.
- 6 M. Bui, C. S. Adjiman, A. Bardow, E. J. Anthony, A. Boston, S. Brown, P. S. Fennell, S. Fuss, A. Galindo, L. A. Hackett, J. P. Hallett, H. J. Herzog, G. Jackson, J. Kemper, S. Krevor, G. C. Maitland, M. Matuszewski, I. S. Metcalfe, C. Petit, G. Puxty, J. Reimer, D. M. Reiner, E. S. Rubin, S. A. Scott, N. Shah, B. Smit, J. P. M. Trusler, P. Webley, J. Wilcox and N. Mac, Dowell, *Energy Environ. Sci.*, 2018, **11**, 1062–1176.
- 7 G. Sneddon, A. Greenaway and H. H. P. Yiu, The Potential Applications of Nanoporous Materials for the Adsorption, Separation, and Catalytic Conversion of Carbon Dioxide, *Adv. Energy Mater.*, 2014, **4**, 1301873–1301892.
- 8 A. A. Olajire, *J. CO<sub>2</sub> Util.*, 2017, **17**, 137–161.
- 9 R. Dawson, E. Stöckel, J. R. Holst, D. J. Adams and A. I. Cooper, *Energy Environ. Sci.*, 2011, **4**, 4239–4245.
- 10 P. Bhanja, A. Modak and A. Bhaumik, *ChemCatChem*, 2019, **11**, 244–257.
- 11 W. Wang, M. Zhou and D. Yuan, *J. Mater. Chem. A*, 2017, **5**, 1334–1347.
- 12 H. A. Patel, J. Byun and C. T. Yavuz, *ChemSusChem*, 2017, **10**, 1303–1317.
- 13 R. Bera, M. Ansari, A. Alam and N. Das, *J. CO<sub>2</sub> Util.*, 2018, **28**, 385–392.
- 14 M. Cox and R. Mokaya, *Sustainable Energy Fuels*, 2017, **1**, 1414–1424.
- 15 S. K. Shukla and J. P. Mikkola, *Phys. Chem. Chem. Phys.*, 2018, **20**, 24591–24601.
- 16 K. M. De Lange and J. R. Lane, *J. Chem. Phys.*, 2011, **135**, 0–8.
- 17 G. Chang, Z. Shang, T. Yu and L. Yang, *J. Mater. Chem. A*, 2016, **4**, 2517–2523.
- 18 M. Li, J. Lei, G. Feng, J. U. Grabow and Q. Gou, *Spectrochim. Acta, Part A*, 2020, **238**, 118424.
- 19 A. C. Legon, *Phys. Chem. Chem. Phys.*, 2017, **19**, 14884–14896.
- 20 X. Tan, L. Kou, H. A. Tahini and S. C. Smith, *Sci. Rep.*, 2015, **5**, 1–8.
- 21 D. Nam, P. De Luna, A. Rosas-hernández, A. Thevenon, F. Li, T. Agapie, J. C. Peters, O. Shekhah, M. Eddaoudi and E. H. Sargent, Molecular enhancement of heterogeneous CO<sub>2</sub> reduction, *Nat. Mater.*, 2020, **19**, 266–276.
- 22 B. Dash, *J. Mol. Model.*, 2018, **24**, 1–8.
- 23 P. Kanoo, R. Matsuda, H. Sato, L. Li, N. Hosono and S. Kitagawa, *Chem. – Eur. J.*, 2020, **26**, 2148–2153.
- 24 S. S. Rao and S. P. Gejji, *J. Phys. Chem. A*, 2016, **120**, 1243–1260.
- 25 L. M. Azofra and S. Scheiner, Tetrel, chalcogen, and CH···O hydrogen bonds in complexes pairing carbonyl-containing molecules with 1, 2, and 3 molecules of CO<sub>2</sub>, *J. Chem. Phys.*, 2015, **142**, 034307-1–034307-9.
- 26 L. Lodeiro, R. Contreras and R. Ormazábal-Toledo, *J. Phys. Chem. B*, 2018, **122**, 7907–7914.
- 27 X. Y. Luo, X. Fan, G. L. Shi, H. R. Li and C. M. Wang, *J. Phys. Chem. B*, 2016, **120**, 2807–2813.
- 28 H. Y. Li, Y. X. Lu, X. Zhu, C. J. Peng, J. Hu, H. L. Liu and Y. Hu, *Sci. China: Chem.*, 2012, **55**, 1566–1572.



- 29 X. Zhu, Y. Lu, C. Peng, J. Hu, H. Liu and Y. Hu, *J. Phys. Chem. B*, 2011, **115**, 3949–3958.
- 30 V. Chernikova, O. Shekhah, Y. Belmabkhout and M. Eddaoudi, DOI: 10.1021/acsanm.0c00909.
- 31 S. K. Das, P. Bhanja, S. K. Kundu, S. Mondal and A. Bhaumik, *ACS Appl. Mater. Interfaces*, 2018, **10**, 23813–23824.
- 32 C. Liao, Z. Liang, B. Liu, H. Chen, X. Wang and H. Li, *ACS Appl. Nano Mater.*, 2020, **3**, 2889–2898.
- 33 Y. Fu, Z. Wang, S. Li, X. He, C. Pan, J. Yan and G. Yu, *ACS Appl. Mater. Interfaces*, 2018, **10**, 36002–36009.
- 34 O. Buyukcakir, S. H. Je, S. N. Talapaneni, D. Kim and A. Coskun, *ACS Appl. Mater. Interfaces*, 2017, **9**, 7209–7216.
- 35 Y. P. Zhao, Y. Li, C. Y. Cui, Y. Xiao, R. Li, S. H. Wang, F. K. Zheng and G. C. Guo, *Inorg. Chem.*, 2016, **55**, 7335–7340.
- 36 J. Wang, W. Sng, G. Yi and Y. Zhang, *Chem. Commun.*, 2015, **51**, 12076–12079.
- 37 A. E. Sadak, *Microporous Mesoporous Mater.*, 2021, **311**, 110727.
- 38 V. A. Online, M. M. Unterlass, F. Emmerling, M. Antonietti and J. Weber, From dense monomer salt crystals to CO<sub>2</sub> selective microporous polyimides *via* solid-state polymerization, *Chem. Commun.*, 2014, **50**, 430–432.
- 39 O. Buyukcakir, S. H. Je, D. S. Choi, S. N. Talapaneni, Y. Seo, Y. Jung, K. Polychronopoulou and A. Coskun, *Chem. Commun.*, 2016, **52**, 934–937.
- 40 J. Ding, C. Zheng, L. Wang, C. Lu, B. Zhang, Y. Chen, M. Li, G. Zhai and X. Zhuang, *J. Mater. Chem. A*, 2019, **7**, 23337–23360.
- 41 C. Hua, B. Chan, A. Rawal, F. Tuna, D. Collison, J. M. Hook and D. M. D'Alessandro, *J. Mater. Chem. C*, 2016, **4**, 2535–2544.
- 42 W. Hui, X. M. He, X. Y. Xu, Y. M. Chen, Y. Zhou, Z. M. Li, L. Zhang and D. J. Tao, *J. CO<sub>2</sub> Util.*, 2020, **36**, 169–176.
- 43 G. Chen, X. Huang, Y. Zhang, M. Sun, J. Shen, R. Huang, M. Tong, Z. Long and X. Wang, *Chem. Commun.*, 2018, **54**, 12174–12177.
- 44 Y. Zhang, K. Zhang, L. Wu, K. Liu, R. Huang, Z. Long, M. Tong and G. Chen, *RSC Adv.*, 2020, **10**, 3606–3614.
- 45 T. Škorjanc, D. Shetty, M. A. Olson and A. Trabolsi, *ACS Appl. Mater. Interfaces*, 2019, **11**, 6705–6716.
- 46 Y. Zhang, K. Liu, L. Wu, H. Zhong, N. Luo, Y. Zhu, M. Tong, Z. Long and G. Chen, *ACS Sustainable Chem. Eng.*, 2019, **7**, 16907–16916.
- 47 Y. Chen, R. Luo, Q. Xu, J. Jiang, X. Zhou and H. Ji, *ACS Sustainable Chem. Eng.*, 2018, **6**, 1074–1082.
- 48 Y. Leng, D. Lu, P. Jiang, C. Zhang, J. Zhao and W. Zhang, *Catal. Commun.*, 2016, **74**, 99–103.
- 49 C. Hua, B. Chan, A. Rawal, F. Tuna, D. Collison, J. M. Hook and D. M. D'Alessandro, *J. Mater. Chem. C*, 2016, **4**, 2535–2544.
- 50 T. Lu, J. Zhang, Q. Gou and G. Feng, *Phys. Chem. Chem. Phys.*, 2020, **22**, 8467–8475.
- 51 S. J. Grabowski, *Struct. Chem.*, 2019, **30**, 1141–1152.
- 52 T. Škorjanc, D. Shetty, F. Gándara, L. Ali, J. Raya, G. Das, M. A. Olson and A. Trabolsi, *Chem. Sci.*, 2020, **11**, 845–850.
- 53 A. Bauzá, I. Alkorta, J. Elguero, T. J. Mooibroek and A. Frontera, *Angew. Chem.*, 2020, **132**, 17635–17640.
- 54 N. Manoranjan, D. H. Won, J. Kim and S. I. Woo, *J. CO<sub>2</sub> Util.*, 2016, **16**, 486–491.
- 55 S. Zahedi and E. Safaei, *J. CO<sub>2</sub> Util.*, 2020, **42**, 101308.
- 56 X. Jiang, F. Gou, X. Fu and H. Jing, *J. CO<sub>2</sub> Util.*, 2016, **16**, 264–271.
- 57 G. Das, T. Škorjanc, S. K. Sharma, F. Gándara, M. Lusi, D. S. Shankar Rao, S. Vimala, S. Krishna Prasad, J. Raya, D. S. Han, R. Jagannathan, J. C. Olsen and A. Trabolsi, *J. Am. Chem. Soc.*, 2017, **139**, 9558–9565.
- 58 A. L. Myers and J. M. Prausnitz, *AIChE J.*, 1965, **11**, 121–127.
- 59 R. Parajuli, *Curr. Sci.*, 2016, **110**, 495–498.
- 60 J. Roeser, K. Kailasam and A. Thomas, *ChemSusChem*, 2012, **5**, 1793–1799.
- 61 J. Liu, G. Zhao, O. Cheung, L. Jia, Z. Sun and S. Zhang, *Chem. – Eur. J.*, 2019, **25**, 9052–9059.
- 62 H. Li, X. Feng, P. Shao, J. Chen, C. Li, S. Jayakumar and Q. Yang, *J. Mater. Chem. A*, 2019, **7**, 5482–5492.

