

Double ZIF-L structures with exceptional CO₂ capacity

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Abstract

Carbon dioxide emission is an emerging problem nowadays and new methods are designed for its control. In this article, a report on the formation of zeolitic imidazole framework with an apparent double leaf-like morphology DZIF-L is given. The special structure of the materials prevents from aggregation of the particles providing remarkable CO₂ capacity. At 0.1 MPa the CO₂ uptake was 2.99 ± 0.06 mmol/g. The capacity of synthesized material is higher than that of any other structure that was so far identified between single ZIF-L and ZIF-8. Fourier transform infrared (FT-IR), X-ray diffraction (XRD), scanning electron microscopy (SEM) and Brunauer-Emmett-Teller surface area analysis were used to characterize the material.

Key words: zeolitic imidazole framework, carbon dioxide, uptake, adsorption

1. Introduction

The rapid increase of the population and resulting energy consumption contribute to a high emission of pollutants to the atmosphere, from which carbon dioxide is an emerging problem. Therefore, there is a great necessity to develop new effective separation technologies. In recent decades a lot of focus was put on new solvents like ionic liquids or deep eutectic solvents and their use in membrane separation process as well as mixed matrix membranes filled with metal organic frameworks (MOFs). Mixed matrix membranes can incorporate several types of fillers, like zeolites [1–3], silica, activated carbon [4], carbon molecular sieves [5,6], metal organic frameworks (MOFs) [7] and other. Metal-organic frameworks are crystalline materials with high surface area and porosity that form a network of metal ion node coordinated to organic ligands. They are obtained in the reaction of metal salts and organic linkers, like imidazoles, carboxylates etc. which have oxygen or nitrogen atoms built in. Typically, MOFs are obtained by solvothermal method, where the organic and metal precursors are dissolved in polar solvents like water or alcohol [8] and simply mixed to make the product that precipitates from the solution.

Among MOFs there is a large group of materials based on Zn or Co that together with imidazole ligand constitute large molecular structures called zeolitic imidazole frameworks (ZIFs). The bond angle in ZIFs is similar to that in zeolites therefore ZIFs present many characteristics specific for zeolites like stability, high surface area and crystallinity [9] and at the same time advantages of MOFs. Unlike some MOFs ZIFs can be obtained easier and cheaper and are stable in moist conditions and at high temperatures. ZIFs has been widely studied due to the simplicity of the synthesis procedure, sorption capacity and potential in use as a filler for gas separation membranes.

21 Even though the preparation procedure seems to be simple, it should be carefully developed, because
22 concentration of chemicals, solvent type, pH, agitation speed, temperature, additives [10], aging etc. can
23 have a remarkable effect on the ZIF type, its structure, shape and size. Mainly ZIF-8 is studied in the
24 literature, but lately two-dimensional leaf-like shape ZIF-L gained attention. There are several types of
25 ZIF-L reported in the literature, flower-like, hierarchical and single cushion-shape ZIF-L, which is the
26 most frequently examined [11–13].

27 Single ZIF-L are mostly studied in the membrane systems. One of the examples is H₂/CO₂ separation
28 examined by Yang et al. The authors obtained selectivity of ~208 [14]. Pebax membranes incorporating
29 ZIF-L for CO₂/CH₄ separation with the selectivity reaching 19 were also used [15]. Low et al. used ZIF-
30 L nanoflakes in polyethersulfone ultrafiltration membrane [11]. Valencia et al. used leaf-like zeolite
31 imidazole framework foams for carbon dioxide capture with the capacity of 0.75 mmol/g for 50% ZIF-
32 L in the foam, for pure powder CO₂ capacity was 0.9 mmol/g at 298 K and 1 bar [16]. Similar results
33 for carbon dioxide capacity of single ZIF-L were obtained by Chen et al. [17]. The authors proved higher
34 CO₂ capacity of ZIF-L (0.94 mmol/g) than that of ZIF-8 (0.68 mmol/g), ZIF-95 and ZIF-100.

35 In the literature more complex forms of ZIF-L can also be found, these are flower-shaped and
36 hierarchical shapes. Synthesis of flower shaped ZIF-L was reported by Wang et al [18]. CO₂ capacity of
37 hierarchical ZIF-L was determined by Ding et al at the level of 1.56 mmol/g. Park et al examined wide
38 range of different ZIFs and reported that ZIF-8 can be obtained by crystal transformation of ZIF-L [19].
39 Moreover, in research focused on single ZIF-L, a propeller-shaped double structures occur as a defect.
40 In some studies the CO₂ uptake of single ZIF-L occurred to be higher than that of ZIF-8 [17] and lower
41 than that of hierarchical and flower-shaped ZIF-L [18,20], for that reason this research focused on
42 obtaining the least complex three-dimensional ZIF-L structure, namely double ZIF-L (DZIF-L). This
43 structure should limit aggregation in comparison to single ZIF-L and ZIF-8 that tend to agglomerate
44 forming a dense layer. Since ZIF-L are often dedicated to membrane systems, such behaviour would
45 decrease the permeability of resulting membrane and double ZIF-L could resist from aggregation and
46 may be capable of forming oriented porous surface. In this regard, we expect that this special double
47 leaf like shape has potential in gas separation applications.

48 2. Experimental

49 2.1. Preparation of DZIF-L

50 Hydrothermal method for DZIF-L fabrication was used. The molar ratio of the components was set at
51 1:8:2250, accordingly for Zn²⁺:Im:H₂O. Zn²⁺ ions originated from Zn(NO₃)₂·6H₂O, supplied by
52 Chempur Poland, Im source was 2-methylimidazole (99%) from Acros Organics and methanol (99.8%)
53 from Avantor Performance Materials Poland S.A. All chemicals were used without further purification.
54 The water solutions of the components were prepared at 298 K and mixed together for the reaction. The
55 reaction mixture was stirred with a speed of 500 rpm for 5 hours at 288 K. The resulting precipitate was
5 then twice washed with deionised water and twice with methanol, each time being collected by
6 centrifugation (4000 rpm for 10 minutes). Then the sample was dried in a vacuum oven at 343 K
7 overnight.
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1 2.2. Characterization



63
64 Prior to the measurements samples were degassed under vacuum at 423 K for 24 h. Nitrogen adsorption
65 isotherms and total pore volumes were measured using Micromeritics Gemini V Analyzer at 77 K.
66 Nitrogen adsorption curves were determined in the range of P/P_0 from 0.01 to 0.98. Specific surface area
67 was calculated using the Brunauer–Emmett–Teller (BET) linear equation in the approximate relative
68 pressure range from P/P_0 0.05 to 0.3. Total pore volume was calculated at P/P_0 0.95.

69 The morphology of the samples with particle size analysis was investigated by the Schottky field
70 emission scanning electron microscope SEM (FEI Quanta FEG 250) with an ET secondary electron
71 detector. The beam acceleration voltage was kept at 10 kV. The samples were coated with gold before
72 imaging.

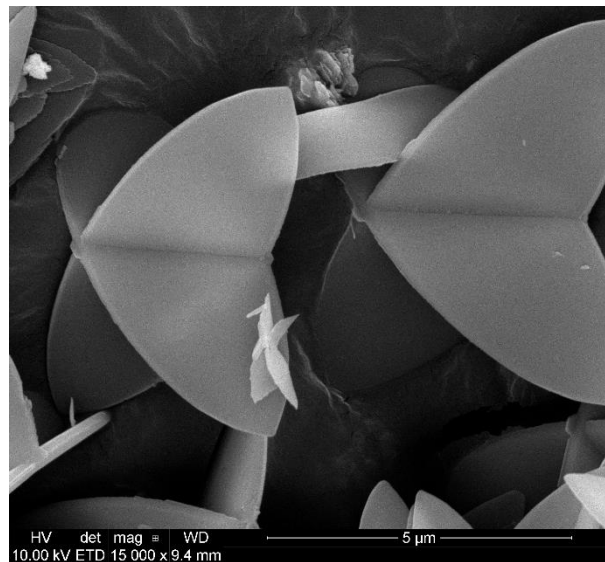
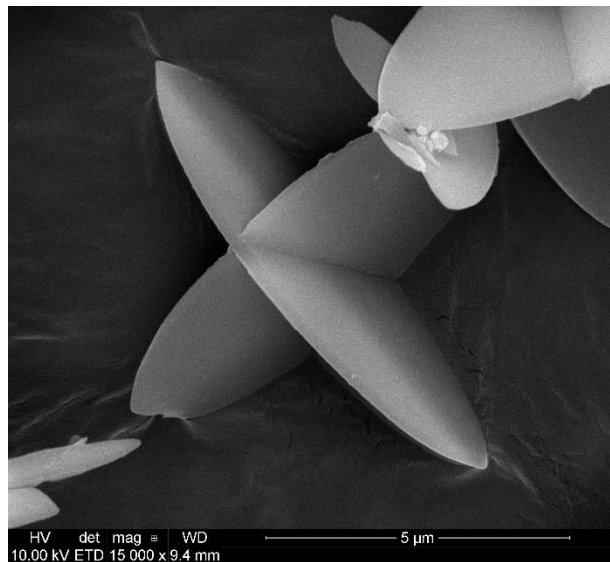
73 X-ray diffraction measurements were made using Cu-K α radiation on a Rigaku Miniflex 600. XRD data
74 was obtained within the angle range of 5-50 degrees operating at a scanning rate of 1° min^{-1} .

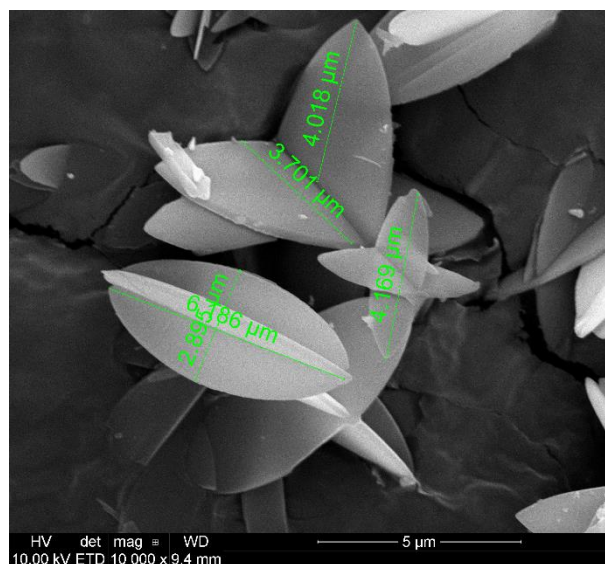
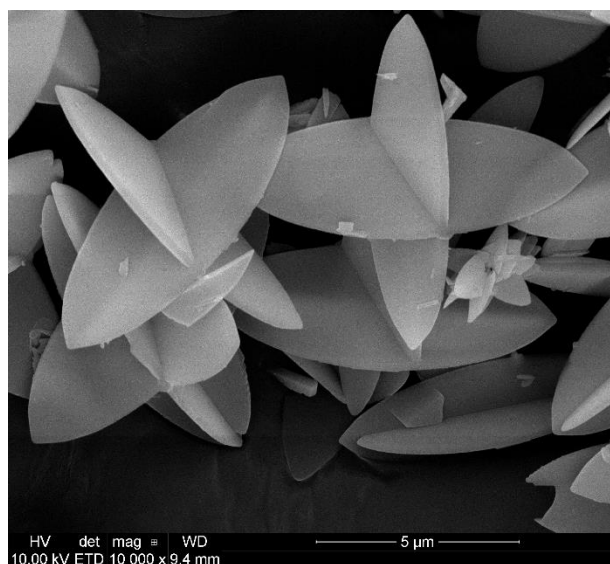
75 The Fourier transform infrared spectrum was recorded in transmittance mode with cm^{-1} spectra cl
76 resolution using ThermoSCIENTIFIC Nicolet iS10.

77 The CO $_2$ adsorption capacity was determined using volumetric method as described in the literature
78 [18,20]. Briefly, the capacity was determined at 298 K up to 250 kPa. Prior to the test, dry and degassed
79 samples were placed in the testing chamber and kept under vacuum for 12 h at 373 K. The samples were
80 cooled to 298 K and pure CO $_2$ was introduced to reach equilibrium. The equilibrium pressure was
81 recorded when the value did not change over 4 hours.

83 3. Results and discussion

84 The sample morphology was characterized by SEM. The material is white and is a 3D framework with
85 well-defined leaf-shaped crystals, composed of two ZIF-L structures crossing each other along the long
86 or short axis. The morphology is well defined and different from that of single ZIF-L and flower-shaped
87 ZIL-L. As shown in Figure 1 the average nominal size of the DZIF-L was found to be 7.8 μm along the
88 long axis and 3.4 μm along the short axis. The main difference between these two identified structures
89 is the ration of length to width

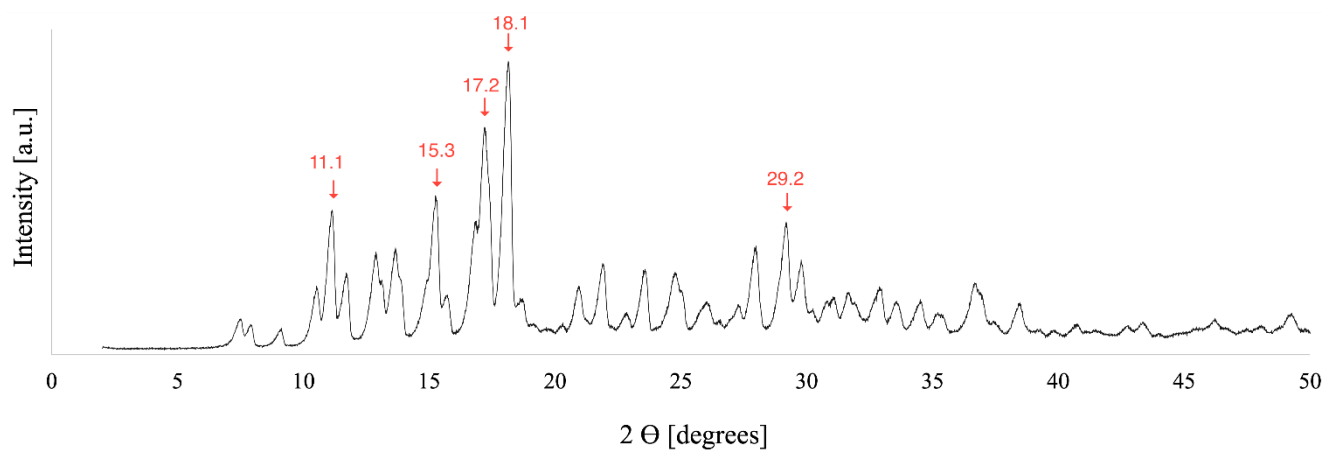




90
91 **Figure 1 SEM micrograph of the DZIF-L**

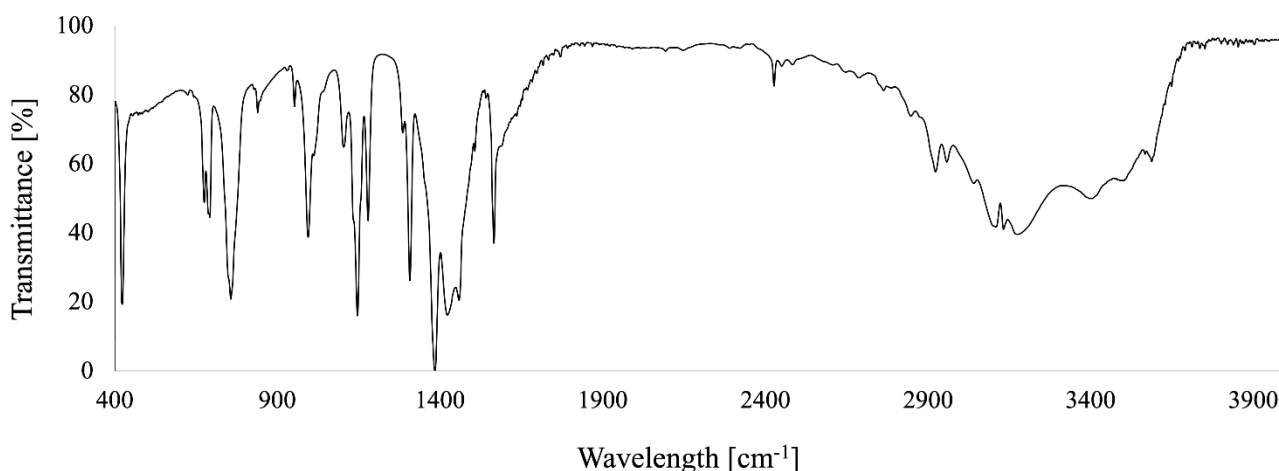
92
93 The structure of obtained material was analysed using XRD as shown in Figure 2 a). All the diffraction
94 peak positions agree well with the spectra reported in the literature for ZIF-L with relatively strongest
95 XRD peaks observed at 2θ of 11.1° , 15.3° , 17.2° , 18.1° , 29.2° that stay in agreement with the several
96 reports from ZIF-L studies [21,22].
97

a)



b)





98
99 **Figure 2 a) XRD pattern and b) FTIR spectrum of DZIF-L**

100
101 As shown in Figure 2 b) the chemical structure of the DZIF-L was verified by FTIR spectroscopy.
102 Presence of the characteristic peaks for C=N, C-N, CH, and Zn-N was confirmed and agrees well with
103 ones reported in the literature for ZIF-L.

104 The results indicated the main bands at 422 cm⁻¹, 692 cm⁻¹, 758 cm⁻¹, 995 cm⁻¹, 1147 cm⁻¹, 1179 cm⁻¹,
105 1307 cm⁻¹, 1386 cm⁻¹, 1566 cm⁻¹ and 2426 cm⁻¹. The absorption band at 422 cm⁻¹ represents stretching
106 of Zn-N. The bands in the spectral region of 600-800 cm⁻¹ are associated with bending of the imidazole
107 ring outside the plane, those in 900-1350 region with in-plane bending. Peaks at 1307 cm⁻¹, 1179 cm⁻¹,
108 1147cm⁻¹ and 995 cm⁻¹ are associated with C-N stretching vibrations. Peaks at 1386 cm⁻¹ and 758 cm⁻¹
109 can be assigned to CH aromatic bending. The C=N bonds are represented by peak at about 1566 cm⁻¹
110 and are attributed to stretching vibration. The peak at about 2426 cm⁻¹ is ascribed to N-H···N hydrogen
111 bond, while the broad band from 2350 to 3700 N-H···N results from the bridging the ZIF-L layers and
112 the N-H group in methylimidazole [19].

113 For the obtained DZIF-L, N₂ adsorption measurement was performed to determine the specific surface
114 area, as presented in Figure 4. The isotherm is of type II according to the IUPAC classification, which
115 indicates the macroporous structure of the material.
116

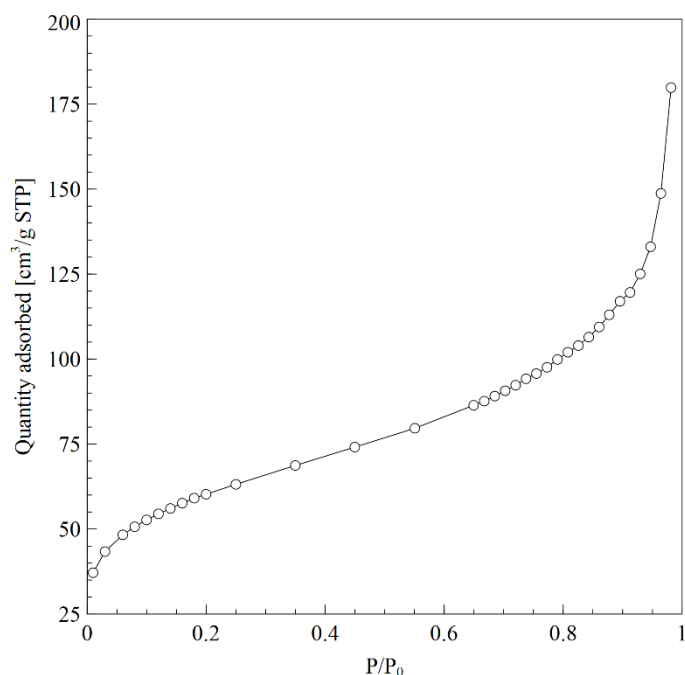


Figure 3 Exemplary N₂ adsorption isotherm of the DZIF-L

The specific surface area of the obtained DZIF-L samples was $223 \pm 10 \text{ m}^2/\text{g}$ and is in a good agreement with the values presented in the literature for individual ZIF-L structures. The area is larger than that observed for leaf-like ZIF-L and lower than that reported for flower-shaped structures and ZIF-8. For single ZIF-L, Chen et al. reported $161 \text{ m}^2/\text{g}$ and micropore volume of $0.066 \text{ cm}^3/\text{g}$ [17], by Deacon et al. reported $93 \text{ m}^2/\text{g}$ for single ZIF-L and 1651 for ZIF-8 [23]. Hierarchical structures were proved to have $304 \text{ m}^2/\text{g}$ [20]. Still, values reported by different authors vary. Low et al. obtained $18 \text{ m}^2/\text{g}$ and porosity of $0.02 \text{ cm}^3/\text{g}$ for single ZIF-L [19]. Kahn et al. obtained surface area of $2.5 \text{ m}^2/\text{g}$ and pore volume of $0.0034 \text{ cm}^3/\text{g}$ for 2D ZIF-L and $1472 \text{ m}^2/\text{g}$ and $0.6067 \text{ cm}^3/\text{g}$ for ZIF-8 [24].

Within this study, for DZIF-L we obtained total pore volume of $0.188 \pm 0.02 \text{ cm}^3/\text{g}$ at P/P_0 of 0.95, which is compliant with the values reported by other researchers, higher than the values obtained for single ZIF-L and lower than the values reported for ZIF-8.



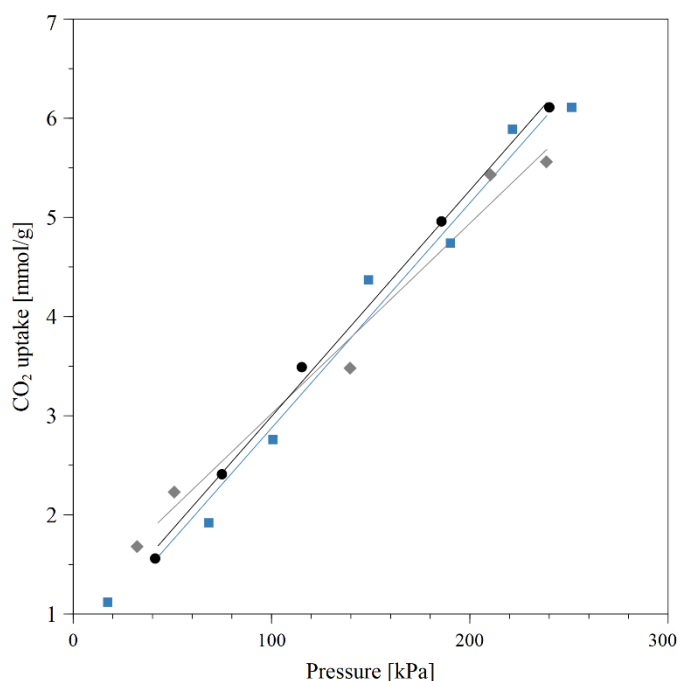


Figure 4 Adsorption isotherm of CO₂ by DZIF-L at 298 K (●; ■; ◆ represent experimental points of three experiments)

The adsorption isotherms of CO₂ by the DZIF-L are shown in Figure 4. In the three experiments at 0.1 MPa the CO₂ uptake was 3.02, 3.05 and 2.91 mmol/g, resulting in the average capacity of 2.99 ± 0.06 mmol/g. The capacity of synthesized material is higher than that of any other structure that was so far identified between single ZIF-L and ZIF-8 (Figure 5).

Only Shi et al. obtained comparable capacity of ZIF-8. The authors performed test on CO₂ adsorption capacity of ZIF-8 obtained at different conditions and reported capacity in a range 2.18 – 3.04 g/mmol. The structure of 3.04 mmol/g capacity was synthesized at 358 K [25]. Flower-shaped ZIF-L synthesized by Wang et al. exhibited CO₂ uptake of 1.15 mmol/g at 298 K and 0.1 MPa [18]. Chen et al. reported 0.94 mmol/g uptake for single ZIF-L and 0.68 mmol/g for ZIF-8 [17]. Hierarchical ZIF-L structures, which is between flower-shaped ZIF and double- ZIF-L, obtained by Ding et al. exhibited 1.56 mmol/g uptake with 304 m²/g of surface area [20]. Double ZIF-L presents higher CO₂ capacity than single one. This is attributed to the structure, and anti-aggregation properties [18]. The special structure of the particles prevents from stacking together as it is seen in case of leaf-like ZIF. Moreover ZIF-L has a smaller pore size and higher density of metal atoms per unit volume than ZIF-8 [17] and despite the larger surface area of ZIF-8, double ZIF-L has a comparable CO₂ adsorption capacity because of the special shape and cavity. It enables a strong interaction between CO₂ and the 2-methylimidazole originating from the short distance of O atom in CO₂ and H atoms in methylimidazole [17].



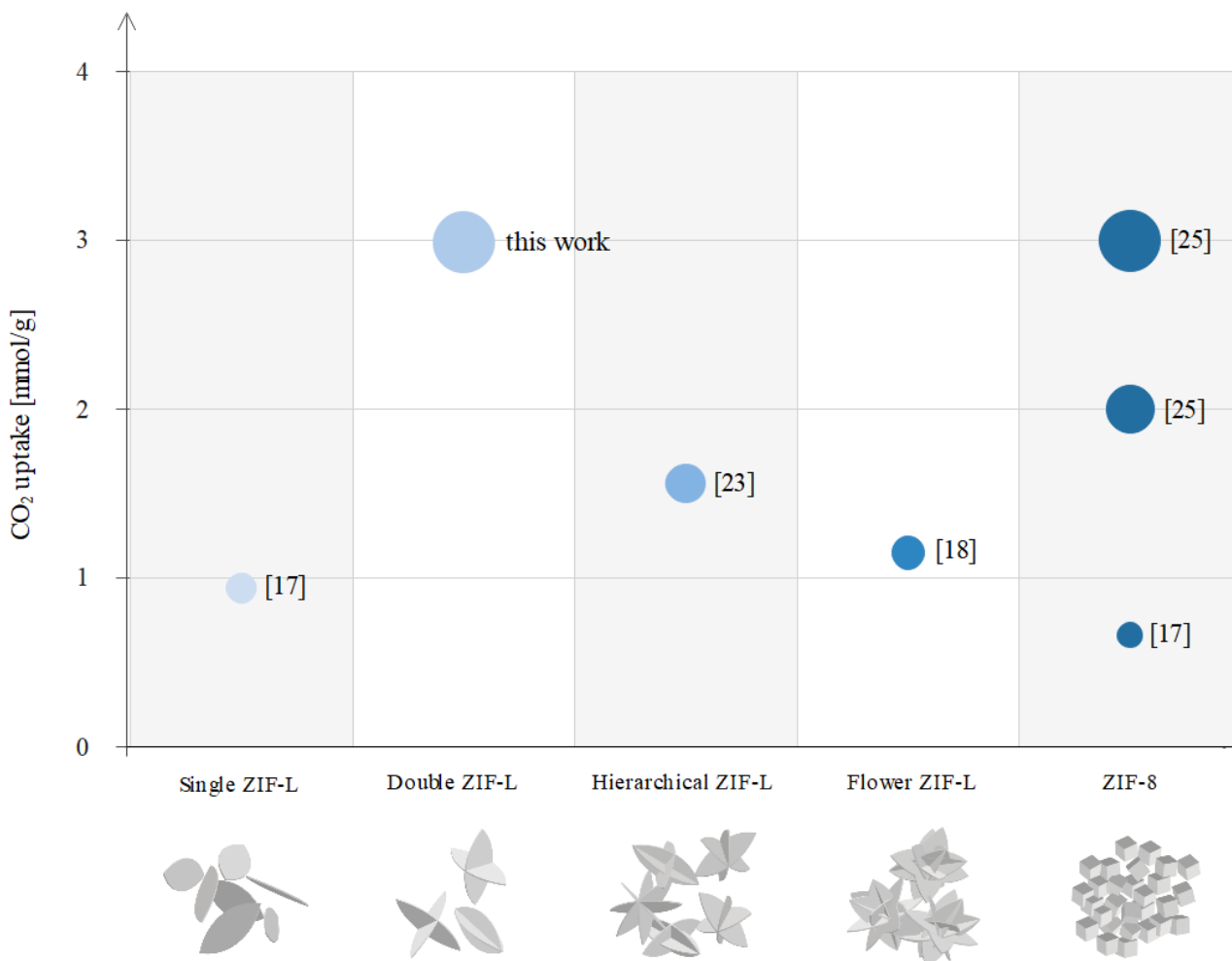


Figure 5 CO₂ uptake of individual ZIF-L structures

4. Conclusions

To our best knowledge it is the first time when the apparent DZIF-L structure was obtained for CO₂ capture. Literature data show that on the transition route from ZIF-L to ZIF-8 there also three other structures that can be distinguished, namely flower-shaped ZIF-L, hierarchical ZIF-L and double ZIF-L obtained within this study. There is only one report in which the authors described ZIF-8 with CO₂ capacity at the same level [25] as capacity of DZIF-L obtained in this research. In general, the specific surface area increases as the ZIF-L transforms to the ZIF-8, but CO₂ capacity is higher for ZIF-L than for ZIF-8 and the intermediate structures present even higher capacity than both ZIF-L and ZIF-8. From all the structures that can be distinguished DZIF-L presented the best performance. Agglomeration can be the reason for lower capacity of single ZIF-L and ZIF-8 as the molecules stick to each other forming a dense layer that limits adsorption capacity. Within the study we succeeded in obtaining the least complex three-dimensional ZIF-L structure, that reduces aggregation and thus enables high adsorption. Since ZIF-Ls are often dedicated to membrane systems, such structure may be capable of forming oriented porous surface which can enhance permeability of resulting membrane. In this regard, we expect that the obtained double ZIF-L structure, which was proven to have remarkable CO₂ capacity in

171 comparison to ZIF-8, hierarchical, flower-shaped and single ZIF-L, has the potential in gas separation
172 applications.

174 **Declaration of Competing Interest**

175 The authors declare that they have no known competing financial interests or personal relationships that
176 could have appeared to influence the work reported in this paper.

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182 **Author contributions**

183 Iwona Cichowska-Kopczyńska conceived and supervised the project, planned the experiments,
184 performed the sorption experiments, contributed to the data analysis, interpretation and wrote the paper.
185 Joanna Mioduska synthesized the material, performed analyses including BET analyses, FTIR, XRD,
186 contributed to the data analysis, interpretation and paper writing. Jakub Karczewski performed the
187 analyses.

189 **References**

- 190 [1] T.W. Pechar, S. Kim, B. Vaughan, E. Marand, M. Tsapatsis, H.K. Jeong, C.J. Cornelius,
191 Fabrication and characterization of polyimide-zeolite L mixed matrix membranes for gas
192 separations, *J. Memb. Sci.* 277 (2006) 195–202. <https://doi.org/10.1016/j.memsci.2005.10.029>.
- 193 [2] M.G. Sürer, N. Baç, L. Yilmaz, Gas permeation characteristics of polymer-zeolite mixed matrix
194 membranes, *J. Memb. Sci.* 91 (1994) 77–86. [https://doi.org/10.1016/0376-7388\(94\)00018-2](https://doi.org/10.1016/0376-7388(94)00018-2).
- 195 [3] B. Ozturk, F. Demirciyeva, Comparison of biogas upgrading performances of different mixed
196 matrix membranes, *Chem. Eng. J.* 222 (2013) 209–217.
197 <https://doi.org/10.1016/j.cej.2013.02.062>.
- 198 [4] M. Anson, J. Marchese, E. Garis, N. Ochoa, C. Pagliero, ABS copolymer-activated carbon
199 mixed matrix membranes for CO₂/CH₄ separation, *J. Memb. Sci.* 243 (2004) 19–28.
200 <https://doi.org/10.1016/j.memsci.2004.05.008>.
- 201 [5] R. Mahajan, W.J. Koros, Separation Materials, *Ind. Eng. Chem. Res.* 39 (2000) 2692–2696.
- 202 [6] D.Q. Vu, W.J. Koros, S.J. Miller, Mixed matrix membranes using carbon molecular sieves: I.
203 Preparation and experimental results, *J. Memb. Sci.* 211 (2003) 311–334.
204 [https://doi.org/10.1016/S0376-7388\(02\)00429-5](https://doi.org/10.1016/S0376-7388(02)00429-5).
- 205 [7] M. Arjmandi, M. Pakizeh, Mixed matrix membranes incorporated with cubic-MOF-5 for
206 improved polyetherimide gas separation membranes: Theory and experiment, *J. Ind. Eng.
207 Chem.* 20 (2014) 3857–3868. <https://doi.org/10.1016/j.jiec.2013.12.091>.
- 208 [8] J.L.C. Rowsell, O.M. Yaghi, Metal-organic frameworks: A new class of porous materials,
209 *Microporous Mesoporous Mater.* 73 (2004) 3–14.
210 <https://doi.org/10.1016/j.micromeso.2004.03.034>.
- 211 [9] M.S. Mirqasemi, M. Homayoonfal, M. Rezakazemi, Zeolitic imidazolate framework
212 membranes for gas and water purification, Springer International Publishing, 2020.
213 <https://doi.org/10.1007/s10311-019-00933-6>.
- 214 [10] J. Cravillon, R. Nayuk, S. Springer, A. Feldhoff, K. Huber, M. Wiebcke, Controlling Zeolitic
215 Imidazolate Framework Nano- and Microcrystal Formation: Insight into Crystal Growth by



Time-Resolved In Situ Static Light Scattering, *Chem. Mater.* 23 (2011) 2130–2141.

<https://doi.org/10.1021/cm103571y>.

- [11] Z.X. Low, A. Razmjou, K. Wang, S. Gray, M. Duke, H. Wang, Effect of addition of two-dimensional ZIF-L nanoflakes on the properties of polyethersulfone ultrafiltration membrane, *J. Memb. Sci.* 460 (2014) 9–17. <https://doi.org/10.1016/j.memsci.2014.02.026>.
- [12] C. Zhang, J. Yan, T. Ji, D. Du, Y. Sun, L. Liu, X. Zhang, Y. Liu, Fabrication of highly (110)-Oriented ZIF-8 membrane at low temperature using nanosheet seed layer, *J. Memb. Sci.* 641 (2022) 119915. <https://doi.org/10.1016/j.memsci.2021.119915>.
- [13] Z. Zhong, J. Yao, R. Chen, Z. Low, M. He, J.Z. Liu, H. Wang, Oriented two-dimensional zeolitic imidazolate framework-L membranes and their gas permeation properties, *J. Mater. Chem. A* 3 (2015) 15715–15722. <https://doi.org/10.1039/c5ta03707g>.
- [14] K. Yang, S. Hu, Y. Ban, Y. Zhou, N. Cao, M. Zhao, Y. Xiao, W. Li, W. Yang, ZIF-L membrane with a membrane-interlocked-support composite architecture for H₂/CO₂ separation, *Sci. Bull.* 66 (2021) 1869–1876. <https://doi.org/10.1016/j.scib.2021.05.006>.
- [15] W. Zhu, X. Li, Y. Sun, R. Guo, S. Ding, Introducing hydrophilic ultra-thin ZIF-L into mixed matrix membranes for CO₂/CH₄ separation, *RSC Adv.* 9 (2019) 23390–23399. <https://doi.org/10.1039/c9ra04147h>.
- [16] L. Valencia, H.N. Abdelhamid, Nanocellulose leaf-like zeolitic imidazolate framework (ZIF-L) foams for selective capture of carbon dioxide, *Carbohydr. Polym.* 213 (2019) 338–345. <https://doi.org/10.1016/j.carbpol.2019.03.011>.
- [17] R. Chen, J. Yao, Q. Gu, S. Smeets, C. Baerlocher, H. Gu, D. Zhu, W. Morris, O.M. Yaghi, H. Wang, A two-dimensional zeolitic imidazolate framework with a cushion-shaped cavity for CO₂ adsorption, *Chem. Commun.* 49 (2013) 9500–9502. <https://doi.org/10.1039/c3cc44342f>.
- [18] S. Wang, B. Zang, Y. Chang, H. Chen, Synthesis and carbon dioxide capture properties of flower-shaped zeolitic imidazolate framework-L, *CrystEngComm* 21 (2019) 6536–6544. <https://doi.org/10.1039/c9ce00833k>.
- [19] Z.X. Low, J. Yao, Q. Liu, M. He, Z. Wang, A.K. Suresh, J. Bellare, H. Wang, Crystal transformation in zeolitic-imidazolate framework, *Cryst. Growth Des.* 14 (2014) 6589–6598. <https://doi.org/10.1021/cg501502r>.
- [20] B. Ding, X. Wang, Y. Xu, S. Feng, Y. Ding, Y. Pan, W. Xu, H. Wang, Hydrothermal preparation of hierarchical ZIF-L nanostructures for enhanced CO₂ capture, *J. Colloid Interface Sci.* 519 (2018) 38–43. <https://doi.org/10.1016/j.jcis.2018.02.047>.
- [21] C.J. Wijaya, S. Ismadji, H.W. Aparamarta, S. Gunawan, Facile and green synthesis of starfruit-like ZIF-L, and its optimization study, *Molecules* 26 (2021). <https://doi.org/10.3390/molecules26154416>.
- [22] C. Huang, H. Zhang, K. Zheng, Z. Zhang, Q. Jiang, J. Li, Two-dimensional hydrophilic ZIF-L as a highly-selective adsorbent for rapid phosphate removal from wastewater, *Sci. Total Environ.* 785 (2021). <https://doi.org/10.1016/j.scitotenv.2021.147382>.
- [23] A. Deacon, L. Briquet, M. Malankowska, F. Massingberd-Mundy, S. Rudić, T. I. Hyde, H. Cavaye, J. Coronas, S. Poulston, T. Johnson, Understanding the ZIF-L to ZIF-8 transformation from fundamentals to fully costed kilogram-scale production, *Commun. Chem.* 5 (2022) 1–10. <https://doi.org/10.1038/s42004-021-00613-z>.
- [24] I.U. Khan, M.H.D. Othman, A.F. Ismail, N. Ismail, J. Jaafar, H. Hashim, M.A. Rahman, A. Jilani, Structural transition from two-dimensional ZIF-L to three-dimensional ZIF-8 nanoparticles in aqueous room temperature synthesis with improved CO₂ adsorption, *Mater. Charact.* 136 (2018) 407–416. <https://doi.org/10.1016/j.matchar.2018.01.003>.
- [25] Z. Shi, Y. Yu, C. Fu, L. Wang, X. Li, Water-based synthesis of zeolitic imidazolate framework-8 for CO₂ capture, *RSC Adv.* 7 (2017) 29227–29232. <https://doi.org/10.1039/c7ra04875k>.

