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LITERATURE STUDY ON THE SCREENING OF Al-MOFs POROUS MATERIAL FOR DIMETHYL ETHER (DME) GAS PURIFICATION

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Abstract

Renewable dimethyl ether (DME) gas is expected to replace LPG due to the high demand for domestic fuel gas and the shortage of LPG supply. DME properties are closely identical to that of LPG. DME gas can be produced directly and indirectly from various sources, including coal, natural gas, and other readily available biomass. The synthetic DME gas produces by-product gases, mainly CO_2. Thus, purification of DME is needed. Al-MOF is proposed to be one of many candidates for CO_2 gas absorption. A literature review was conducted in this study to screen some potential Al-MOF based on scientific peer-reviewed articles published in the last decade. The data were gathered by developing research questions using PICO(S) analysis. Particularly, this study highlights the effect of ligands on pore sizes, the effect of the amine group on absorption capacity, and the thermal stability of Al-MOF. This preliminary study finds several potential Al-MOFs suitable for the task. Based on this study, the NH2-MIL-53(Al) and NH2-MIL-101(Al) are highlighted as having the potency to be used in the DME purification process. However, further studies, including evidence-based gas separation experiments, are compulsory and need to be performed before this Al-MOF is applied to the DME purification process on a bigger scale.

Keywords: Aluminum; CO_2; Separation; DME; MOF

1. INTRODUCTION

The Indonesian Ministry of Energy and Mineral Resources (ESDM) targets to replace the consumption of liquid petroleum gas (LPG) with dimethyl ether (DME) (ESDM, 2020). This is due to the increasing demand for LPG supply, which reaches 7 tons per year, of which 70% is imported and expected to rise by 17.4 tons by 2050 (Yuliarita et al., 2020; Murti et al., 2021). The DME is currently one of the alternative fuels to replace LPG (Anggarani et al., 2014), targeted to reduce the increasing dependence on LPG imports in Indonesia (Ramadhani et al., 2020). It is a better option for fuel gas, as it emits less CO and NOx in the exhaust gases and has physical properties similar to LPG. Consequently, it can be used as an LPG substitute (Saravanan et al., 2017; Panigrahy and Mishra, 2018). DME can be produced from various sources of natural gas, coal, or other biomass abundantly available in nature (Seddon, 2011; Yuliarita et al., 2020).

DME is an organic gas (C_2H_6O) with a boiling point of -24°C, close to LPG's -30°C. It is a gas at room temperature (Kurnia'Arifushidqi et al., 2021). It has a very high critical temperature (400°K) and can be liquefied at room temperature. Its density in the liquid phase is close to LPG (Murti et al., 2021). It has a molecular weight of 46.684 g mol^{-1}, a critical pressure of 54 bar, a critical temperature of 401°K, a boiling point of 249°K at 1 atm, a density of 0.663 $g.cm^{-3}$ at 298°K, a viscosity of 0.15 cP or 0.15 $kg.m.s^{-1}$, equivalent to the viscosity of propane and butane (LPG), and surface tension of 11.731 $dyne.cm^{-1}$ (Mohan et al., 2017). The DME has a diameter of around 0.62 nm (Omojola et al., 2020).

$CO + 2H_2 \rightleftharpoons CH_3OH \quad \Delta H° = -90.6$ kJ/mol (eq. 1)
$2CH_3OH \rightleftharpoons CH_3OCH_3 + H_2O \quad \Delta H° = -23.5$ kJ/mol (eq. 2)

Direct synthesis of DME:
$3CO + 3H_2 \rightleftharpoons CH_3OCH_3 + CO_2$

The DME synthesis process consists of the conversion of natural gas hydrocarbons into synthetic

gases (CO, CO_2, and H_2O), and the second stage can be completed either indirectly via methanol synthesis or directly (Mevawala et al., 2017; Kurnia'Arifushidqi et al., 2021; Merkouri et al., 2022). The dehydration of methanol produced from syngas is the foundation of the industry's well-developed DME production process. In the first phase, syngas is turned into methanol (eq. 1), which is then transformed into DME (eq. 2) in a subsequent reactor (Mota, 2021). However, DME products still mix with impurities such as CO_2. So, it needs purification, for example gas adsorption using porous materials.

Porous materials such as silica, zeolite, and metal-organic frameworks (MOFs) can be explored as candidates for the purification of DME gas, particularly by separating the CO_2 by-products. However, MOFs are more promising because Post-synthetic Modification (PSM) is easier for their ligands and metal ions, so the gas adsorption ability can be enhanced as desired (Yin et al., 2022). Metal-organic frameworks (MOFs), a type of solid-state material, have emerged as modular and functional porous materials with the potential to address a wide range of long-term energy and environmental concerns regarding sustainability (Alezi et al., 2015; Wang et al., 2017; Towsif Abtab et al., 2018). MOFs have some structural advantages over standard porous materials like activated carbons and zeolites, like high porosity, large surface area, variable pore size and geometry, and functionalized pore surface (Li et al., 2019; Lin et al., 2020; Kumari et al., 2021). Their structure can be modified according to the expected applications (Fan et al., 2021).

MOFs are one of many synthetic porous materials consisting of metal ions linked together by organic linking ligands with strong bonds that has a high surface area (Tian et al., 2016; Gulati and Kakkar, 2018; Adegoke and Maxakato, 2021). MOFs have a specific surface area of 1000 to 10.000 $m^2.g^{-1}$, far exceeding that of most commonly used porous materials such as zeolite and carbon (J. Li et al., 2019; Fan et al., 2021; Elsayed et al., 2021). Nevertheless, most MOFs are made from divalent cations, which can produce MOFs with high crystallinity, but the instability of the divalent cations of the MOFs can limit their application, especially if they are used as an adsorbent (Wu et al., 2020). Therefore, one way to overcome this problem is to choose a larger metal cation charge because, from a thermodynamic point of view, a higher cation charge will lead to a stronger metal-ligand bond, which is the main determining factor for the thermal stability of the MOFs (Wu et al., 2020).

Aluminum has higher positive charge than divalent metals (Wu et al., 2020). The Al-MOF production process is relatively easy and has a high yield, which can be carried out by solvothermal or hydrothermal methods (Adegoke & Maxakato, 2021). It can be prepared at relatively low temperatures and raw material costs (J. Li et al., 2021; Z. Liu et al., 2021). In addition, the availability of aluminum in Indonesia is abundant (Kementerian ESDM RI - Booklet, 2020). It can also be obtained from the recycling process to be sustainable for MOFs (Joshi et al., 2019). The aluminum recycling process can usually be done by casting using sand-casting to produce new recycled aluminum material (Fasya & Iskandar, 2015). The Al-MOFs types have high porosity, like the CAU-10-NH_2 used for acetylene absorption (C_2H_2), a nonpolar organic compound almost the same size as DME. It absorbs 4.3 mmol cm^{-3} at a pressure of 1 bar and 298°K and even enhances to 4.1 mmol cm^{-3} at 0.5 bar or reaches 95%. The amine group of the ligand influences the absorption capacity (Zhang et al., 2022).

A systematic review was conducted to reveal the material characteristics of Al-MOFs that have the potential to purify DME. Furthermore, the results of this study are expected to provide added value for aluminum processing and provide scientific references to the government's policy plan to convert LPG to DME commercially for low-emission gas fuels.

This study gathered the data by developing research questions using PICO(S) analysis (Table 1.) to combine previous research findings with specific criteria specifications.

Table 1. PICO(S) analysis

PICO(S)	Analysis
Population	Al-MOFs
Intervention	CO_2 absorption or separation to Al-MOF
Comparison	DME absorption to Al-MOF
Outcome	Ligands, absorption capacity, conditions, pore sizes
Study type	Qualitative

Preferred Reporting Items for Systematic Review and Meta-analyses Statement (PRISMA) guidelines were also used to conduct the study. Indonesian and English keywords were used for the literature searches on international database sources such as ScienceDirect, ACS Publications, Proquest, SpringerLink, Royal Chemistry Society, and Wiley Online Library with keywords: "CO_2 Absorption" or "CO_2 Separation" or "CO_2 Purification" and "Porous Materials" and "Al-MOF".

The inclusion studies of abstract and full-text selection was done using the Rayyan AI application. To be considered for inclusion, the study had to meet the following criteria: 1) Recent studies (within the last ten years; 2) Primary research article; 3) Metal-Organic Frameworks studies; 4) Pore size, absorption capacity, ligands, conditions, regeneration, yields, and pore sizes.

Data was collected and inputted in a table from each study. The following information was included in the table: pore size, absorption capacity, ligands, conditions, regeneration, yields, and pore sizes. The data were then tabulated in the form of a PRISMA diagram chart (Figure 1).

In order to find as much relevant research as feasible for a systematic review, it is important to map

out the sensitivity and precision of the studies (Table 2) as follow:

Sensitivity: $\frac{\mathbf{A}}{A+B}$; Precision: $\frac{\mathbf{A}}{A+C}$

Table 2. The sensitivity and precision of screening study

	Identified	Unidentified
Relevant	**A** (n=22)	**B** (n=1354)
Irrelevant	**C** (n=58)	**D** (n=0)

Sensitivity: $\frac{\mathbf{A}}{A+B} = \frac{22}{22+1354}$ = 1.59%

Precision: $\frac{\mathbf{A}}{A+C} = \frac{22}{22+58}$ = 27.5%

Note:
- Identified Relevant (A): appropriate study outcomes/population and outcome.
- Unidentified Relevant (B): not selected/limited access/fee access.
- Irrelevant Identified (C): studies under 10 years old and or wrong outcome
- Irrelevant Unidentified (D): not population

The primary data were then evaluated for completeness using these criteria: ligands, absorption capacity, conditions, and pore sizes (Table 3). Moreover, following the Scopus standards, the validity of the journal's quality was evaluated using the primary data completeness of outcomes (Table 4.).

Table 3. Identification of primary data for inclusion studies based on completeness of outcomes (*)

Outcomes	Complete	Incomplete
(n=22)	9	13
%	**40.9**	**59.1**

(*) Ligands, Absorption Capacity, Conditions, Pore Sizes

Table 4. The Scopus standards of primary data

Scopus Standard	Q1	Q2	Q3	Q4
n=22	17	4	0	1

All these parameters were used to identify and discuss the possible candidates of Al-MOFs for CO_2 separation, based on: (1) the effect of ligands on pore sizes, (2) the effect of the amine group of the ligand on the absorption capacity, (3) the thermal stability of Al-MOF.

2. RESULTS AND DISCUSSION

2.1 Data Collection of Inclusion Study

The PICO(S) method was performed prior to the search of studies by database journals with the goal of identifying the research criteria to be used. Based on

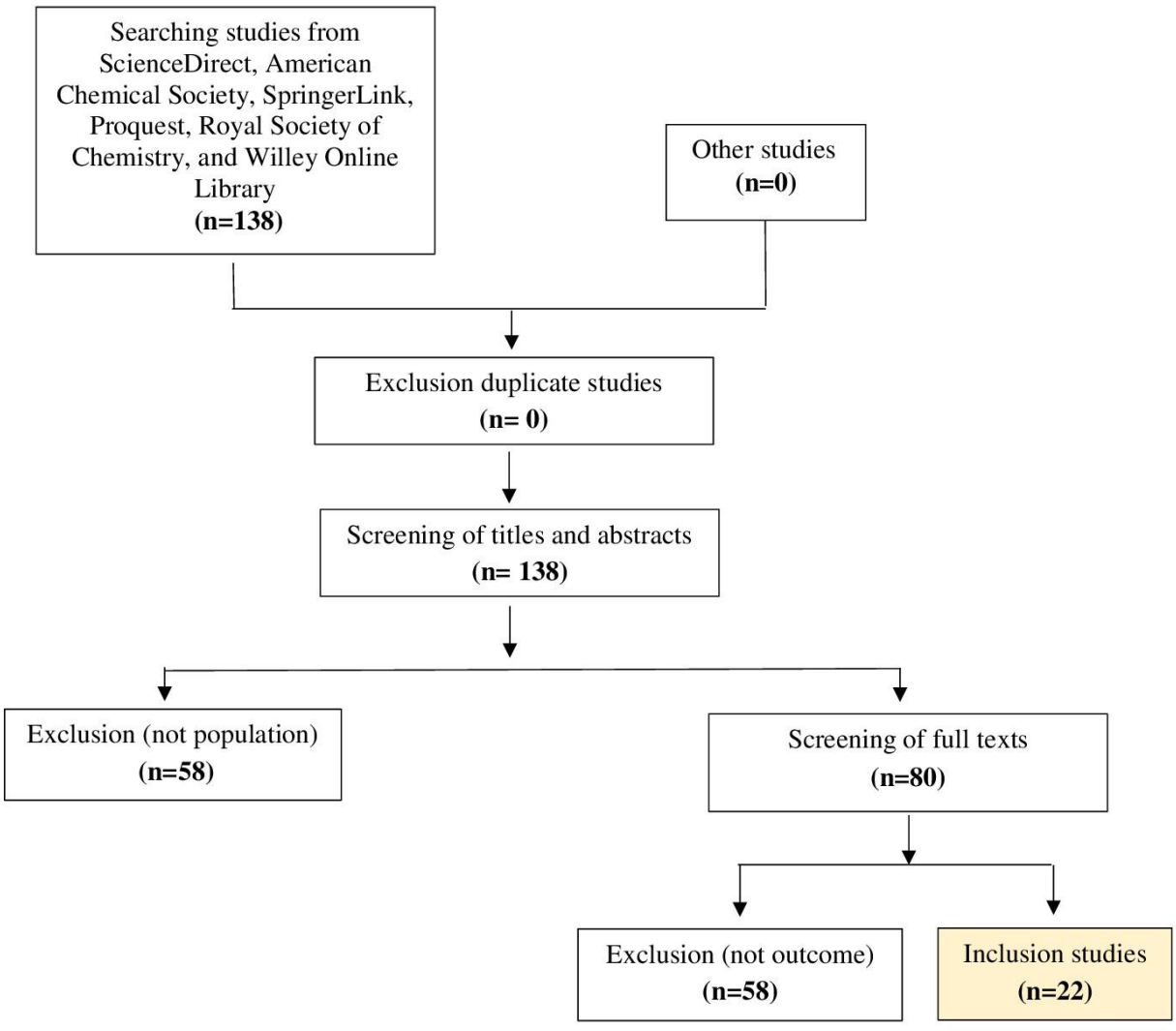

Figure 1. PRISMA diagram chart

selected keywords, 1492 papers from the last ten years (2012-2022) from ScienceDirect, ACS, Proquest, SpringerLink, ACS Publications, RSC Publications, and Wiley Online Publications were obtained. Among those 1492 papers, only 138 papers have related content (based on title and abstract) with the objective of this review. Moreover, 58 articles were also excluded because the authors do not have an open access permit. Thus, the exclusion resulted in 80 articles for full-text screening. Based on the information availability of ligand's type, absorption capacity, adsorption conditions, and pore sizes in each paper, only 22 papers are included in this review.

2.2 Data Processing

Based on Table 5, the increasing sensitivity of study inclusion will reduce precision. Consequently, the resulting studies will have many irrelevant studies. Therefore, higher-quality inclusion investigations can be achieved by maximizing sensitivity while retaining the precision of search studies (Higgins et al., 2022). In this systematic review, the results of primary data are concluded based on completeness, with findings that the Scopus standard of the Al-MOFs characteristics from primary data sets are presented in the Table 6.

Table 5. The qualitative synthesis result of inclusion studies

n = 138							**Inclusion=22**
Sensitivity	**Precision**	**Primary Data (n=22)**	**Validity (*)**				**Outcome (n=9)**
			Q1	**Q2**	**Q3**	**Q4**	
1.59%	27.5%	100%	17	4	0	1	40.9%

** Based on SCImago*

Table 6. Detail information of selected Al-MOFs (*)

No	Al-MOFs	Ligands	Absorption Capacity (mmol/g)	Condition (K/Bar)	Pore Size (nm)	Regeneration (**)	Yield	Ref
1	Al-PMOF(Co)	Porphine-5,10,15,20-tetrakis (benzoic acid)	3.32	273/1	0.5-1	***NI***	41 %	(Shang et al., 2022)
2	Al-FUM	Fumaric acid	2.1	303/1	***NI***	75-83 %	***NI***	(Coelho et al., 2016)
3	MIL-96(Al)	Benzene tricarboxylic acid	2	303/1	***NI***	20%	***NI***	(Benoit et al., 2013)
4	MIL-53(Al)	Benzene dicarboxylic acid	3.84	303/1-10	0.9	***NI***	***NI***	(Abedini et al., 2014)
			2.36	298/1	1.42	9x	***NI***	(Panda et al., 2020)
			2.3	303/1	***NI***	86-99.6%	***NI***	(Ferreira et al., 2015)
			2.16	298/1	0.7-1	***NI***	48-91	(Sun et al., 2022)
			2.10	298/1	1.41	8x	***NI***	(Panda et al., 2020)
			2.02	298/5	0.7-0.8	***NI***	***NI***	(Ahmadi Feijani et al., 2015)
5	NH_2-MIL-53(Al)	2-aminobenzene-1,4-dicarboxylic acid	14.3	303/10	***NI***	***NI***	***NI***	(X. Y. Chen et al., 2012)
			4.3	303/3.5	***NI***	***NI***	***NI***	(D. Li et al., 2021)
			3.75	303/1-10	0.83	***NI***	***NI***	(Abedini et al., 2014)
			2.65	298/5	***NI***	13x	***NI***	(Zhu et al., 2016)
			2.33	308/10	***NI***	***NI***	***NI***	(Tien-Binh et al.,

								2015)
			1.86	298/9	***NI***	***NI***	***NI***	(Sabetghadam et al., 2016)
			1.85	298/5	***NI***	***NI***	***NI***	(Ahmadi Feijani et al., 2015)
			1.56	308/3	***NI***	***NI***	***NI***	(Rodenas, van Dalen, García-Pérez, et al., 2014a)
			1.23	298/5	***NI***	***NI***	***NI***	(Feijani et al., 2015)
			1.06	308/3	***NI***	***NI***	***NI***	(Rodenas, van Dalen, García-Pérez, et al., 2014a)
6	NH_2-MIL-101(Al)	2-aminobenzene-1,4-dicarboxylic acid	2.9	298.15–348.15/1	***NI***	***NI***	***NI***	(Babar et al., 2021)
			1.70	308/3	***NI***	***NI***	***NI***	(Rodenas, van Dalen, Serra-Crespo, et al., 2014b)
			1.11	308/3	***NI***	***NI***	***NI***	(Rodenas, van Dalen, Serra-Crespo, et al., 2014b)
7	MIL-68(Al)	Benzene dicarboxylic acid	2.24	373/1	***NI***	***NI***	***NI***	(Dong et al., 2016)
			0.87	308/3	***NI***	NI	69-95	(Seoane et al., 2013)
8	CAU-10-NH_2	5-aminoisophthalic acid	2.5	298/1	***NI***	***NI***	***NI***	(Zhang et al., -2022)
9	CAU-10-H	*m*- benzene dicarboxylate	2	298/1	0.48-0.6	***NI***	***NI***	(Zhang et al., 2022)
10	MIL-53 (Al)-Mn	Benzene dicarboxylic acid	13.17	273/9.5	1.57	***NI***	***NI***	(Abid et al., 2021)
			12.76	273/9.5	1.56	***NI***	***NI***	
			3.24	273/1	1,53	***NI***	***NI***	
			3.15	273/1	1.57	***NI***	***NI***	
			3.02	273/1	1.56	***NI***	***NI***	
			2.92	273/1	1.54	***NI***	***NI***	
			2.84	298/1	1,53	***NI***	***NI***	
			2.83	298/1	1.57	***NI***	***NI***	
			2.67	298/1	1.56	***NI***	***NI***	
			2.58	298/1	1.54	***NI***	***NI***	

(*) sorted in order of high to low absorption capacity; (**) in percentage or in cycles
NI = No information

2.3 Discussion

2.3.1 Effect of ligands on pore sizes

The size of DME is around 6 Å (Omojola et al., 2020). However, the main target for DME purification is the separation of CO_2, which traps CO_2 in the pore. Herein, the pore sizes of Al-MOFs are screened based on the similarity to the size diameter of CO_2, which ranges from 3.3 Å (Ahmadi et al., 2015; Feijani et al., 2015). The pore size used to trap CO_2 is between 3-5 Å. Hence, codes A and I can be recommended for CO_2 gas absorption (Table 7).

Moreover, the pore size can be altered by modifying the ligands. A rigid or flexible ligand as a linker unit governs the framework stability. Aliphatic linkers are more flexible than the aromatic ones. Thus, Al-MOFs formed by aliphatic linkers are commonly less stable and tend to collapse due to desolvation, although in some cases, interpenetration may form by the flexible aliphatic linkers and hold the structure stronger. Thus, the code B (Table 7) is unfavorable for Al-MOFs candidates.

Table 7. Some candidates of Al-MOF for DME purification (based on CO_2 separation ability)

CODE	Al-MOFs	Ligands	Absorption Capacity (mmol/g)	Condition (K/Bar)	Pore Size (nm)
A	Al-PMOF(Co)	Porphine-5,10,15,20-tetrakis (benzoic acid)	3.32	273/1	0.5-1
B	Al-FUM	Fumaric acid	2.1	303/1	***NI***
C	MIL-96(Al)	Benzene tricarboxylic acid	2	303/1	***NI***
D	MIL-53(Al)	Benzene dicarboxylic acid	3.84	303/1-10	0.9
			2.36	298/1	1.42
			2.3	303/1	***NI***
			2.16	298/1	0.7-1
			2.10	298/1	1.41
			2.02	298/5	0.7-0.8
E	NH_2-MIL-53(Al)	2-aminobenzene-1,4-dicarboxylic acid	14.3	303/10	***NI***
			4.3	303/3.5	***NI***
			3.75	303/1-10	0.83
			2.65	298/5	***NI***
			2.33	308/10	***NI***
F	NH_2-MIL-101(Al)	2-aminobenzene-1,4-dicarboxylic acid	2.9	298.15–348.15/1	***NI***
G	MIL-68(Al)	Benzene dicarboxylic acid	2.24	373/1	***NI***
H	CAU-10-NH_2	5-aminoisophthalic acid	2.5	298/1	***NI***
I	CAU-10-H	*m*- benzene dicarboxylate	2	298/1	0.48-0.6
J	MIL-53 (Al)-Mn	Benzene dicarboxylic acid	13.17	273/9.5	1.57
			12.76	273/9.5	1.56
			3.24	273/1	1,53
			3.15	273/1	1.57
			3.02	273/1	1.56
			2.92	273/1	1.54
			2.84	298/1	1,53
			2.83	298/1	1.57
			2.67	298/1	1.56
			2.58	298/1	1.54

(*) sorted by higher absorption capacity.
NI = No information

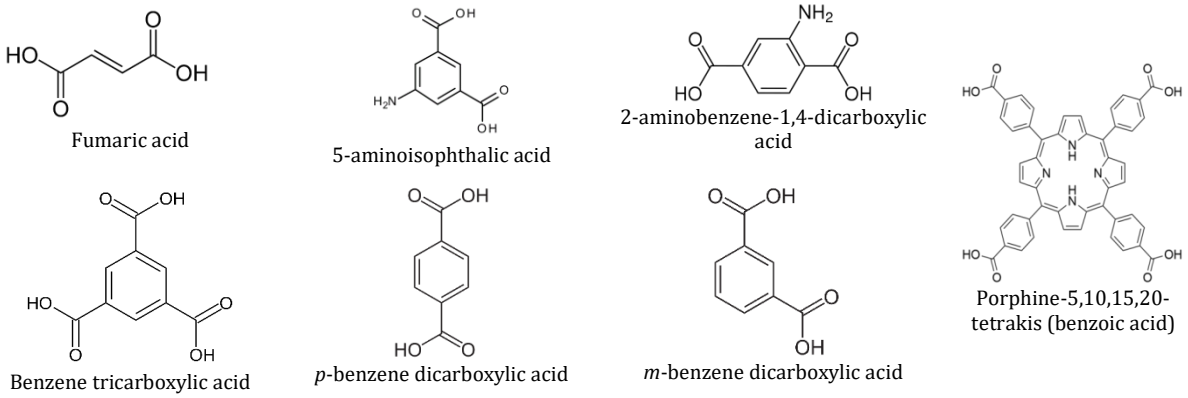

Figure 2. Some organic precursors used in the Al-MOFs as the linkers

2.3.2 *Effect of amine group on absorption capacity*

As shown in Table 7, the Al-MOF codes A, C, D, E, F, G, H, I, and J are possible for CO_2 separation. Another factor is introduced to gain a more selective adsorbent for DME purification, namely the absorption capacity. Only a few candidates mentioned in Table 7 fulfill this criterion, summarized in Table 8 (Codes E, F, and H).

Figure 3 indicates that an amine group, as part of the ligand, enhances CO_2 separation. This is because the amine groups can form hydrogen bond with the oxygen of the CO_2 molecule (–$NH^{\delta+}\cdots{}^{-\delta}O{=}C{=}O^{\delta-}\cdots{}^{+\delta}HN$–). Each amine group on the ligand can bind two CO_2 molecules ($O{=}C{=}O^{\delta-}\cdots{}^{+\delta}H{-}N{-}H^{\delta+}\cdots{}^{-\delta}O{=}C{=}O$) depending on the structure of the ligand and the crystal packing (Figure 4; Figure 5). In other words, the CO_2 molecules are absorbed in the pores due to the additional interaction of the amine group, which eventually enhances the CO_2 absorption capacity. Not only the amine group, when utilizing specific organic linkers, variations of active sites in the pore may also be modified, for example, hydroxyl (–OH) groups. The high electronegativity effect of the O atom of the hydroxyl group (compared to the N atom of amine) may increase the intermolecular interaction between the hydroxyl and CO_2, and as a result, more CO_2 molecules can be adsorbed. In addition, intramolecular interactions may also occur between organic linkers and inorganic units (Figure 6) and enrich the host-guest interaction within the MOF pores.

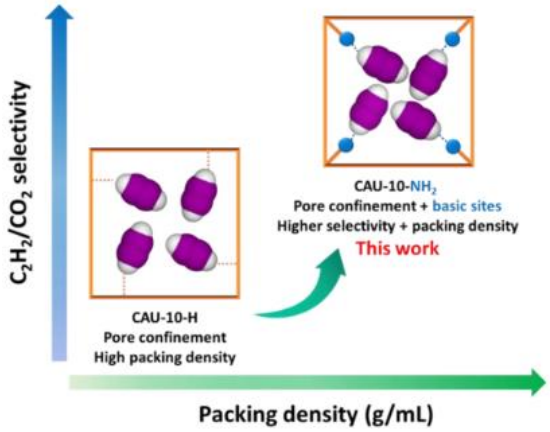

Figure 3. MOFs of amine group shows improved performance (Zhang et al., 2022)

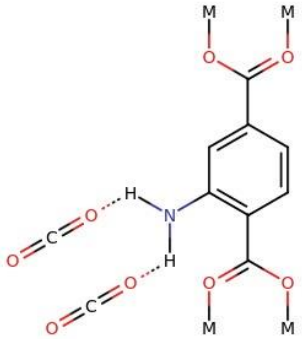

Figure 4. The amine group from the ligan may hold up to two CO_2 molecules

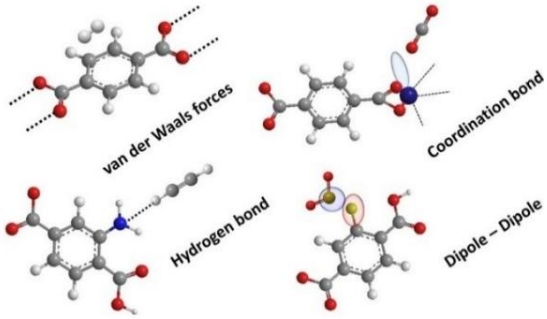

Figure 5. Other possible molecular interactions (Colorado-Peralta et al., 2022)

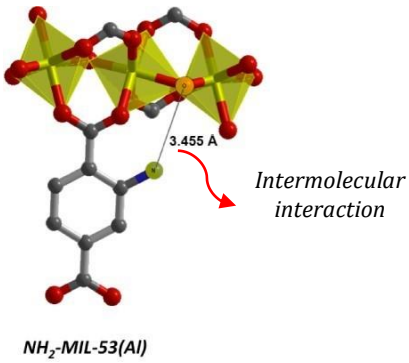

Figure 6. The intermolecular interaction between the linker and inorganic units of NH_2-MIL-53 (Serra-Crespo et al., 2012)

Table 8. Some candidates of Al-MOF for DME purification (based on the CO_2 separation ability)

CODE	Al-MOFs	Ligands	Absorption Capacity (mmol/g)	Condition (K/Bar)	Pore Size (nm)
E	NH_2-MIL-53(Al)	2-aminobenzene-1,4-dicarboxylic acid	14.3	303/10	***NI***
			4.3	303/3.5	***NI***
			3.75	303/1-10	0.83
			2.65	298/5	***NI***
			2.33	308/10	***NI***
F	NH_2-MIL-101(Al)	2-aminobenzene-1,4-dicarboxylic acid	2.9	298.15–348.15/1	***NI***
H	CAU-10-NH_2	5-aminoisophthalic acid	2.5	298/1	***NI***

NI = No information

2.3.3 Thermal stability of Al-MOF

The reported Al-MOF, both with and without utilizing amine-based ligand, frequently shows good thermal stability. In many cases, the decompositions of Al-MOF are reaching temperature of around 300-400 °C (573-673K) or above. This was supported by the TGA analysis of some Al-MOF as shown in Figure 7 and Figure 8. This considerably high stability is due to the fact that most Al-MOF forms 3D polymeric networks and uses rigid bridging ligand. This thermal stability enhances the properties and strongness of Al-MOF to be used as multi-cycles adsorbent in practical use.

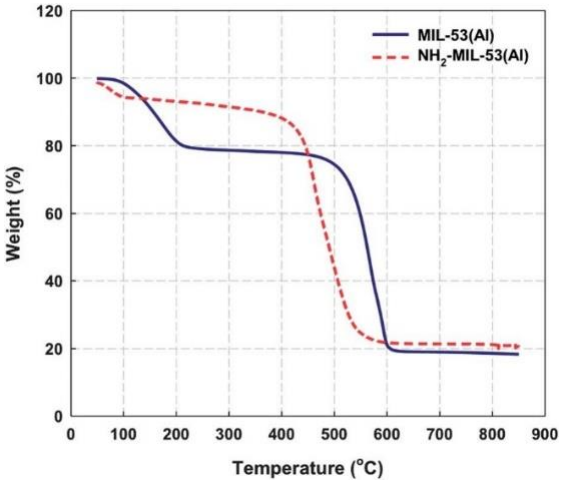

Figure 7. TG Curves of NH_2-MIL-53(Al) (X. Chen et al., 2013)

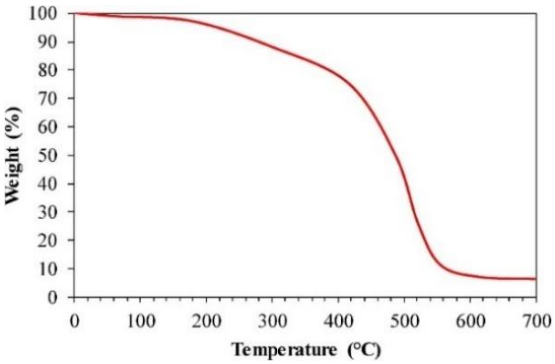

Figure 8. TG Curves of the NH_2-MIL-101(Al) (Babar *et al*., 2021)

Based on the thermal properties criteria, there are two Al-MOFs proposed for the candidate in the DME purifications (Table 9), based on pore size, CO_2 absorption capacity, and thermal stability, namely the NH_2-MIL-53(Al) and NH2-MIL-101(Al). The CAU-10-NH_2 (code H) may need to be considered. However, the thermal analysis of the compound was not found in the paper yet. Preparing the three mentioned Al-MOFs is considerably easy and results in good yield. Moreover, the precursor availability for making the three mentioned Al-MOFs is sustainable. However, further studies, such as computational studies, including evidence-based DME/CO_2 gas separation experiments, are compulsory and need to be performed before this Al-MOF can be applied in the DME purification process on a bigger scale.

Table 9. The proposed candidates of Al-MOFs for DME purification

Al-MOFs	Ligands	CO_2 absorption capacity (mmol/g)	Condition (K/Bar)	Pore Size (nm)
NH_2-MIL-53(Al)	NH_2-BDC	3.75	303/1-10	0.83
NH_2-MIL-101(Al)	NH_2-BDC	2.9	298.15–348.15/1	***NI***

NI = No information

3. CONCLUSION

This study highlights NH_2-MIL-53(Al) and NH_2-MIL-101(Al) as possible alternatives for DME purification based on pore size, CO_2 absorption capacity, and thermal stability. Further investigations, such as computational studies, are needed before the proposed Al-MOF can be applied practically.

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5. REFERENCES

Abedini, R., Omidkhah, M., & Dorosti, F. (2014). Highly permeable poly (4-methyl-1-pentyne)/NH_2-MIL 53 (Al) mixed matrix membrane for CO_2/CH_4 separation. RSC Advances, 4(69), 36522–36537.

Abid, H. R., Rada, Z. H., Liu, L., Wang, S., & Liu, S. (2021). Striking CO_2 capture and CO_2/N_2 separation by Mn/Al bimetallic MIL-53. Polyhedron, 193, 114898.

Adegoke, K. A., & Maxakato, N. W. (2021). Porous metal-organic framework (MOF)-based and MOF-derived electrocatalytic materials for energy conversion. Materials Today Energy, 21, 100816.

Ahmadi Feijani, E., Tavasoli, A., & Mahdavi, H. (2015). Improving gas separation performance of poly (vinylidene fluoride) based mixed matrix membranes containing metal–organic frameworks by chemical modification. Industrial & Engineering Chemistry Research, 54(48), 12124–12134.

Alezi, D., Belmabkhout, Y., Suyetin, M., Bhatt, P. M., Weseliński, Ł. J., Solovyeva, V., Adil, K., Spanopoulos, I., Trikalitis, P. N., Emwas, A.-H., & Eddaoudi, M. (2015). MOF Crystal Chemistry Paving the Way to Gas Storage Needs: Aluminum-Based soc -MOF for CH_4, O_2, and CO_2 Storage. Journal of the American Chemical Society, 137(41), 13308–13318.

Anggarani, R., Wibowo, C. S., & Rulianto, D. (2014). Application of Dimethyl Ether as LPG Substitution for Household Stove. Conference and Exhibition

Indonesia Renewable Energy & Energy Conservation, Jakarta - Indonesia, 47, 227–234.

Babar, M., Mubashir, M., Mukhtar, A., Saqib, S., Ullah, S., Bustam, M. A., & Show, P. L. (2021). Sustainable functionalized metal-organic framework NH_2-MIL-101(Al) for CO_2 separation under cryogenic conditions. Environmental Pollution, 279, 116924.

Benoit, V., Chanut, N., Pillai, R. S., Benzaqui, M., Beurroies, I., Serre, C., Steunou, N., Maurin, G., & Llewellyn, P. L. (2013). A promising metal-organic framework (MOF), MIL-96(Al) for CO_2 separation under humid conditions. Journal of Material Chemistry A, 12.

Brandt, P., Xing, S.-H., Liang, J., Kurt, G., Nuhnen, A., Weingart, O., & Janiak, C. (2021). Zirconium and Aluminum MOFs for Low-Pressure SO_2 Adsorption and Potential Separation: Elucidating the Effect of Small Pores and NH_2 Groups. ACS Applied Materials & Interfaces, 13(24), 29137–29149.

Chen, X., Hoang, V.-T., Rodrigue, D., & Kaliaguine, S. (2013). Optimization of continuous phase in amino-functionalized metal–organic framework (MIL-53) based co-polyimide mixed matrix membranes for CO_2/CH_4 separation. RSC Advances, 3, 24266.

Chen, X. Y., Vinh-Thang, H., Rodrigue, D., & Kaliaguine, S. (2012). Amine-Functionalized MIL-53 Metal–Organic Framework in Polyimide Mixed Matrix Membranes for CO_2/CH_4 Separation. Industrial & Engineering Chemistry Research, 51(19), 6895–6906.

Coelho, J. A., Ribeiro, A. M., Ferreira, A. F. P., Lucena, S. M. P., Rodrigues, A. E., & Azevedo, D. C. S. de. (2016). Stability of an Al-Fumarate MOF and Its Potential for CO_2 Capture from Wet Stream. Industrial & Engineering Chemistry Research, 55(7), 2134–2143.

Colorado-Peralta, R., María Rivera-Villanueva, J., Manuel Mora-Hernández, J., Morales-Morales, D., & Ángel Alfonso-Herrera, L. (2022). An overview of the role of supramolecular interactions in gas storage using MOFs. Polyhedron, 224, 115995.

Dong, X., Liu, Q., & Huang, A. (2016). Highly permselective MIL-68 (Al)/matrimid mixed matrix membranes for CO_2/CH_4 separation. Journal of Applied Polymer Science, 133(22).

Elsayed, E., Saleh, M. M., AL-Dadah, R., Mahmoud, S., & Elsayed, A. (2021). Aluminium fumarate metal-organic framework coating for adsorption cooling application: Experimental study. International Journal of Refrigeration, 130, 288–304.

Fan, W., Zhang, X., Kang, Z., Liu, X., & Sun, D. (2021). Isoreticular chemistry within metal–organic frameworks for gas storage and separation. Coordination Chemistry Reviews, 443, 213968.

Fasya, F., & Iskandar, N. (2015). Melt Loss Dan Porositas Pada Aluminium Hasil Daur Ulang. Jurnal Teknik Mesin, 3(1), 44–50.

Feijani, E. A., Mahdavi, H., & Tavasoli, A. (2015). Poly (vinylidene fluoride) based mixed matrix membranes comprising metal organic frameworks for gas separation applications. Chemical Engineering Research and Design, 96, 87–102.

Ferreira, A. F. P., Ribeiro, A. M., Kulaç, S., & Rodrigues, A. E. (2015). Methane purification by adsorptive processes on MIL-53(Al). Metal-Organic Frameworks for Emerging Chemical Technologies, 124, 79–95.

Gulati, A., & Kakkar, R. (2018). DFT studies on storage and adsorption capacities of gases on MOFs. Physical Sciences Reviews, 3(8). 20170196.

Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch VA (editors). Cochrane Handbook for Systematic Reviews of Interventions version 6.3 (updated February 2022). Cochrane, 2022. Available from www.training.cochrane.org/handbook.

Joshi, J. N., Moran, C. M., Feininger, H. P., Dow, J. M., & Walton, K. S. (2019). Household Aluminum Products as Insoluble Precursors for Directed Growth of Metal–Organic Frameworks. Crystal Growth & Design, 19(9), 5097–5104.

Kementerian ESDM Indonesia. (2020). Booklet Tambang Bauksit 2020. https://www.esdm.go.id/id/booklet/booklet-tambang-bauksit-2020. Retrieved June 21, 2022.

Kementerian ESDM Indonesia, (2020). DME, Alternatif Pengganti LPG [www.esdmmigas.go.id]. Migas.esdm.go.id. https://migas.esdm.go.id/post/read/dme-alternatif-pengganti-lpg, (accessed on 19 June 2022).

Kumari, A., Kaushal, S., & Singh, P. P. (2021). Bimetallic metal organic frameworks heterogeneous catalysts: Design, construction, and applications. Materials Today Energy, 20, 100667.

Kurnia'Arifushidqi, L., Muhammad, I., Rahmawati, Y., & Nurkhamidah, S. (2021). Pra Desain Pabrik Dimetil Eter (DME) dari Gas Alam Menggunakan Metode Indirect Process. Jurnal Teknik ITS, 10(1), F19–F24.

Li, D., Chen, L., Liu, G., Yuan, Z., Li, B., Zhang, X., & Wei, J. (2021). Porous metal–organic frameworks for methane storage and capture: Status and challenges. New Carbon Materials, 36(3), 468–496.

Li, H., Li, L., Lin, R.-B., Zhou, W., Zhang, Z., Xiang, S., & Chen, B. (2019). Porous metal-organic frameworks for gas storage and separation: Status and challenges. Energy Chem, 1(1), 100006.

Li, J., Hurlock, M. J., Goncharov, V. G., Li, X., Guo, X., & Zhang, Q. (2021). Solvent-Free and Phase-Selective Synthesis of Aluminum Trimesate Metal–Organic Frameworks. Inorganic Chemistry, 60(7), 4623–4632.

Li, J., Ye, W., & Chen, C. (2019). Chapter 5—Removal of toxic/radioactive metal ions by metal-organic framework-based materials. In C. Chen (Ed.), Interface Science and Technology, Vol. 29, 217–279. Elsevier.

Lin, R.-B., Xiang, S., Zhou, W., & Chen, B. (2020). Microporous Metal-Organic Framework Materials for Gas Separation. Chemistry, 6(2), 337–363.

Liu, Z., Cheng, C., Han, J., Qi, X., Zhao, Z., & Teng, R. (2021). Dehumidification performance of aluminum fumarate metal organic framework and its composite. Applied Thermal Engineering, 199, 117570.

Merkouri, L.-P., Ahmet, H., Ramirez Reina, T., & Duyar, M. S. (2022). The direct synthesis of dimethyl ether (DME) from landfill gas: A techno-economic investigation. Fuel, 319, 123741.

Mevawala, C., Jiang, Y., & Bhattacharyya, D. (2017). Plant-wide modeling and analysis of the shale gas to dimethyl ether (DME) process via direct and indirect synthesis routes. Applied Energy, 204, 163–180.

Mohan, B., Yang, W., Yu, W., & Tay, K. L. (2017). Numerical analysis of spray characteristics of dimethyl ether and diethyl ether fuel. Clean, Efficient and Affordable Energy for a Sustainable Future, 185, 1403–1410.

Mota, N.-M. O., ElenaAU-Pawelec, BárbaraAU-Fierro, José Luis G. AU-Navarro, Rufino M. TI-Direct Synthesis of Dimethyl Ether from CO_2: Recent Advances in Bifunctional/Hybrid Catalytic Systems. (2021). Catalysts, 11(4), 411.

Murti, G. W., Priyanto, U., Masfuri, I., & Adelia, N. (2021). The Effect of Dimethyl Ether (DME) as LPG Subtitution on Household Stove: Mixture Stability, Stove Efficiency, Fuel Consumption, and Materials Testing. Majalah Ilmiah Pengkajian Industri, 15(2). 77-86.

Omojola, T., Silverwood, I. P., & O'Malley, A. J. (2020). Molecular behaviour of methanol and dimethyl ether in H-ZSM-5 catalysts as a function of Si/Al ratio: A quasielastic neutron scattering study. Catalysis Science & Technology, 10(13), 4305–4320.

Panda, D., Patra, S., Awasthi, M. K., & Singh, S. K. (2020). Lab Cooked MOF for CO_2 Capture: A Sustainable Solution to Waste Management. Journal of Chemical Education, 97(4), 1101–1108.

Panigrahy, S., & Mishra, S. C. (2018). The combustion characteristics and performance evaluation of DME (dimethyl ether) as an alternative fuel in a two-section porous burner for domestic cooking application. Energy, 150, 176–189.

Ramadhani, W. S., Paramudita, I., Lailiyah, Q., & Bakti, P. (2020). Karakteristik Kinerja Kompor Gas LPG Menggunakan Bahan Bakar DME Dengan Variasi Diameter Nozzle dan Tekanan Kerja Kompor. Jurnal Standardisasi, 22(3), 199–210.

Rodenas, T., van Dalen, M., García-Pérez, E., Serra-Crespo, P., Zornoza, B., Kapteijn, F., & Gascon, J. (2014a). Visualizing MOF mixed matrix membranes at the nanoscale: Towards structure-performance relationships in CO_2/CH_4 separation over NH_2-MIL-53 (Al)@ PI. Advanced Functional Materials, 24(2), 249–256.

Rodenas, T., van Dalen, M., Serra-Crespo, P., Kapteijn, F., & Gascon, J. (2014b). Mixed matrix membranes based on NH_2-functionalized MIL-type MOFs: Influence of structural and operational parameters on the CO_2/CH_4 separation performance. Microporous and Mesoporous Materials, 192, 35–42.

Sabetghadam, A., Seoane, B., Keskin, D., Duim, N., Rodenas, T., Shahid, S., Sorribas, S., Guillouzer, C. L., Clet, G., & Tellez, C. (2016). Metal organic framework crystals in mixed-matrix membranes: Impact of the filler morphology on the gas separation performance. Advanced Functional Materials, 26(18), 3154–3163.

Saravanan, K., Ham, H., Tsubaki, N., & Bae, J. W. (2017). Recent progress for direct synthesis of dimethyl ether from syngas on the heterogeneous bifunctional hybrid catalysts. Applied Catalysis B: Environmental, 217, 494–522.

Seddon, D. (2011). 12—Methanol and dimethyl ether (DME) production from synthesis gas. In M. R. Khan (Ed.), Advances in Clean Hydrocarbon Fuel Processing (pp. 363–386). Woodhead Publishing.

Seoane, B., Sebastián, V., Téllez, C., & Coronas, J. (2013). Crystallization in THF: the possibility of one-pot synthesis of mixed matrix membranes containing MOF MIL-68 (Al). Crystal Engineering & Communication, 15(45), 9483–9490.

Serra-Crespo, P., Gobechiya, E., Ramos-Fernandez, E. V., Juan-Alcañiz, J., Martinez-Joaristi, A., Stavitski, E., Kirschhock, C. E. A., Martens, J. A., Kapteijn, F., & Gascon, J. (2012). Interplay of Metal Node and Amine Functionality in NH2-MIL-53: Modulating Breathing Behavior through Intra-framework Interactions. Langmuir, 28(35), 12916–12922.

Shang, S., Yang, C., Sun, M., Tao, Z., Hanif, A., Gu, Q., & Shang, J. (2022). CO_2 capture from wet flue gas using transition metal inserted porphyrin-based metal-organic frameworks as efficient adsorbents. Separation and Purification Technology, 301, 122058.

Sun, L., Yin, M., Li, Z., & Tang, S. (2022). Facile microwave-assisted solvothermal synthesis of rod-like aluminum terephthalate [MIL-53(Al)] for CO_2 adsorption. Journal of Industrial and Engineering Chemistry, 112, 279–286.

Tian, J., Xu, Z.-Y., Zhang, D.-W., Wang, H., Xie, S.-H., Xu, D.-W., Ren, Y.-H., Wang, H., Liu, Y., & Li, Z.-T. (2016). Supramolecular metal-organic frameworks that display high homogeneous and heterogeneous photocatalytic activity for H_2 production. Nature Communications, 7(1), 11580.

Tien-Binh, N., Vinh-Thang, H., Chen, X. Y., Rodrigue, D., & Kaliaguine, S. (2015). Polymer functionalization to enhance interface quality of mixed matrix membranes for high CO_2/CH_4 gas separation. Journal of Materials Chemistry A, 3(29), 15202–15213.

Towsif Abtab, S. M., Alezi, D., Bhatt, P. M., Shkurenko, A., Belmabkhout, Y., Aggarwal, H., Weseliński, Ł. J., Alsadun, N., Samin, U., Hedhili, M. N., & Eddaoudi, M. (2018). Reticular Chemistry in Action: A Hydrolytically Stable MOF Capturing Twice Its Weight in Adsorbed Water. Chemistry, 4(1), 94–105.

Wang, H., Zhu, Q.-L., Zou, R., & Xu, Q. (2017). Metal-Organic Frameworks for Energy Applications. Chem, 2(1), 52–80.

Wu, T., Prasetya, N., & Li, K. (2020). Recent advances in aluminium-based metal-organic frameworks (MOF) and its membrane applications. Journal of Membrane Science, 615, 118493.

Yin, J., Zhang, J., Fu, W., Ran, H., Zhang, Y., Zhang, M., Jiang, W., Li, H., Zhu, W., & Li, H. (2022). Porous liquids for gas capture, separation, and conversion: Narrowing the knowing-doing gap. Separation and Purification Technology, 121456.

Yuliarita, E., Zulkifliani, Z., Atmanto, M. D., Sunarjanto, D., & Lubad, A. M. (2020). Kajian Pemanfaatan Gas DME (Dimethyl Ether) atau Uji Terap Pada Sektor Rumah Tangga Di Wilayah Sumatera Selatan. Lembaran Publikasi Minyak dan Gas Bumi, 54(2), 61–67.

Zhang, X., Lin, R.-B., Wu, H., Huang, Y., Ye, Y., Duan, J., Zhou, W., Li, J.-R., & Chen, B. (2022). Maximizing acetylene packing density for highly efficient C_2H_2/CO_2 separation through immobilization of amine sites within a prototype MOF. Chemical Engineering Journal, 431, 134184.

Zhu, H., Wang, L., Jie, X., Liu, D., & Cao, Y. (2016). Improved Interfacial Affinity and CO_2 Separation Performance of Asymmetric Mixed Matrix Membranes by Incorporating Postmodified MIL-53(Al). ACS Applied Materials & Interfaces, 8(34), 22696–22704.