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Amine (Polyethyleneimine)-modified solid adsorbent for CO₂ capture

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Abstract. The increase in the concentration of carbon dioxide (CO₂) gas in the atmosphere has led to various severe negative consequences. There are numerous methods for the reduction of CO₂ that have been introduced such as chemical and physical absorption, organic liquid scrubbing, amine-based absorption, etc. Adsorption by using solid adsorbents is one of the promising methods that has been widely studied by researchers. The performance of the adsorbents can be enhanced by functionalized with diverse types of promoters. This review is discussing the performance of polyethyleneimine (PEI) as a promoter towards the adsorption of CO₂. To achieve high effective PEI-adsorbents, the percentage of PEI amine loading, type of porous support, temperature, and different flow conditions are among the important parameters that need to be considered. The chemical stability of PEI can be improved through modification crosslinking of PEI. Hence in this review, the effect of amine loading, porous support, temperature, slow condition and crosslinking of PEI to its CO₂ adsorption performance is observed.

1. Introduction

Global warming has been one of the serious worldwide threats for decades as it could contribute to a rising level of seawater [1] and various effects on human health [2]. The growing level of global industries and urbanization have inevitably led to the increasing of CO₂ emissions to the atmosphere [3]. Thus, an effective and low-cost carbon capture and storage (CCS) approach to remove tons of CO₂ gas from the environment is needed to overcome these problems [4]. In recent years, the methods involved in CO₂ capture are pre-combustion, post-combustion, and oxy-fuel combustion [5, 6]. Among these methods, post-combustion is considered the promising method since the process is much simpler compared to the other two methods [6].

In the post-combustion method, the adsorption process by using solid adsorbents has gained increasing attention from researchers [7]. However, the performance of solid adsorbents for practical use is still limited by their low CO₂ uptake capacity and selectivity [8]. Amine-functionalized is one of the promising approaches to increase the performance of these adsorbents towards CO₂ adsorption due to several advantages such as good stability, lower heat regeneration, and high adsorption potential [9, 10]. PEI is one of the amine groups that have been widely used due to its high amino contain and good thermal stability [11]. Due to its beneficial behaviors, there are huge numbers of studies have reported on the use of PEI to enhance the CO₂ uptake of various solid adsorbents such as silica [12, 13], graphene oxide [14], metal oxide [15], metal-organic framework [16, 17], etc.



Several interesting reviews are focusing on the CO₂ capture by numerous solid adsorbents, diverse alteration procedures of solid adsorbents, the latest development on amine-functionalized solid adsorbents for post-combustion CO₂ capture, etc. In this respect, the present review is expected to contribute to a better understanding of the recent progress on numerous PEI-functionalized adsorbents for CO₂ capture, several parameters involved in the reaction process, and the modification of PEI by cross-linking.

2. PEI impregnated adsorbents for CO₂ capture

It is well recognized that the presence of PEI as a promoter could significantly improve the CO₂ adsorption of numerous solid adsorbents. In this respect, various works on the PEI-modified solid adsorbents together with the impact of the reaction parameters on the CO₂ uptake performance of the selected adsorbents will be comprehensively discussed in the next sections. Based on table 1, it is shown there are numerous studies of PEI supported to various types of adsorbents. Mainly from the mesoporous silica based due to its properties that are easy to be introduced to functional support [13]. From the data, it clearly showed the presence of impregnated PEI improves the adsorption capacity for all different types of adsorbents. As presented in Table 1, the functionalization of solid adsorbent with PEI has decreased adsorbent textural properties such as surface area and pore volume. It was associated with the coverage of the adsorbent surface, including porous channel by PEI [20]. Thus, adsorbent with good textural properties such as larger surface area and pore volume will require more PEI to reach optimum quantity and, finally, exhibit greater adsorption capacity. Nevertheless, some other parameters that affect the CO₂ adsorption capacity such as amine loading, porous support, adsorption temperature, and different flow conditions. There is also a study of modification PEI through crosslinking by jeon and coworkers that resulting in improve on CO₂ adsorption in terms stability [18].

Table 1. The summary of studies on PEI functional adsorbents.

Adsorbents	Synthesis method	BET surface area (m ² /g)	BJH Pore Volume (cm ³ /g)	Adsorption flow condition (CO ₂ %: inert @ other gas %)/H ₂ O	CO ₂ uptake (mmol/g)	Stability (mmol/g)	Ref
Metal-organic framework-based adsorbent							
Mesoporous MOF 177	Sono-chemical	2784	1.34	(100:0)/-	0.86 at 298 K	-	[16]
10wt% PEI-MOF 177	Sono-chemical and wet impregnation	690	0.393	(100:0)/-	2.84 at 298 K	-	
Mesoporous PCN-777	Hydrothermal	2008	2.16	(25:75 N ₂)/-	1.13 at 298 K	-	[19]
20% PEI-PCN-777	Hydrothermal and wet impregnation	843	0.37	(25:75 N ₂)/-	1.41 at 298 K	1.40 (5 th cycle)	
Zn/Co ZIF	Mixing and stirring	163	0.72	(100:0)/-	1.07 at 298 K	-	[20]
40wt% PEI-Zn/CoZIF	Mixing and stirring and Wet Impregnation	11	0.05	(100:0)/-	1.82 at 298 K	1.75 (10 th cycle)	
MIL-101	Hydrothermal	3324	1.75	(10:90 He)/-	0.80 at 348 K	-	[21]
70wt% PEI-MIL-101	Hydrothermal	923	0.53	(10:90 He)/-	3.81 at 348 K	3.71 (6 th cycle)	
Silica-based adsorbent							
Mesoporous SBA-15	Cooperative	604	1.192	(44.6: 55.4 N ₂)/-	0.11 at 313 K	-	[12]
Mesoporous SBA-11	Cooperative	356	0.792	(44.6: 55.4 N ₂)/-	0 at 313 K	-	
Disordered porous SiO ₂	Cooperative	256	0.460	(44.6: 55.4 N ₂)/-	0.03 at 313 K	-	

40wt% PEI-SBA-15	Cooperative and wet impregnation	248	0.698	(44.6: 55.4 N ₂)/-	0.90 at 313 K	0.62 (4 th cycle)	
40wt% PEI-SBA-11	Cooperative and wet impregnation	16	0.116	(44.6: 55.4 N ₂)/-	0.60 at 313 K	-	
20wt% PEI-SiO ₂	Cooperative and wet impregnation	65	0.175	(44.6: 55.4 N ₂)/-	0.60 at 313 K	-	
HMS-A	Hydrolysis	736	0.66	(100:0)/-	0.53 at 318 K	-	[22]
50wt% PEI-HMS-A	Hydrolysis and wet impregnation	11	0.02	(100:0)/-	2.40 at 318 K	-	
HMS-C	Calcination	1181	0.96	(100:0)/-	0.31 at 318 K	-	
70wt% PEI-HMS-C	Calcination and wet impregnation	2.1	0.01	(100:0)/-	2.19 at 318 K	-	
SFM-0.83-100-5.2	Modified-microemulsion templating	526.2	1.4	(15:85 N ₂)/-	1.14 at 348 K	-	[23]
50wt% PEI-SFM-0.83-100-5.2	Modified-microemulsion templating and impregnation	-	-	(15:85 N ₂)/-	2.48 at 348 K	2.11 (15 th cycle)	
Mesoporous Monolithic MCM550	Gel-casting and Impregnation method	1088.32	1.00	(100:0)/-	0.65 at 348 K	-	[24]
				(12 v%:88 v% N ₂)/-	-	-	
60wt% PEI-MCM550	Gel-casting and Impregnation method	12.48	0.01	(100:0)/-	2.32 at 348 K	2.30 (5 th cycle)	
				(12 v%:88 v% N ₂)/-	1.89 at 348 K	1.91 (5 th cycle)	
Mesostructured cellular foam silica	-	458	2.07	(100:0)/-	-	-	[18]
50wt% PEI-Silica	Drying and dry impregnation	103	0.58	(100:0)/-	3.20 at 353 K	-	
				(15:85 N ₂)/-	2.86 at 353 K	0.48 (40 th cycle)	
50wt% Cross-linked PEI-Silica	Drying and dry impregnation	151	0.79	(100:0)/-	2.74 at 353 K	-	
				(15:85 N ₂)/-	2.06 at 353 K	1.08 (40 th cycle)	
Mesostructured silica KIL-2	Two-step (aging and solvothermal)	702	1.61	-	0.6 at 363 K	-	[25]
PEI-KIL-2	Two-step and wet impregnation	127	0.35	-	3.6 at 363 K	-	
Mesoporous Si-MCM-41	Hydrothermal and wet impregnation	994	1	(100:0)/-	-	-	[26]
50wt% PEI-MCM-41	Hydrothermal and wet impregnation	6	0	(100:0)/-	2.26 at 373 K	1.82 (6 th cycle)	
Metal Oxide-based adsorbent							
MgO	Sol-gel	350	0.414	(99.9:0.01 N ₂)/-	0.68 at 303 K	-	[15]
PEI-MgO	Sol-gel and Impregnation	72	0.178	(99.9:0.01 N ₂)/-	0.54 at 303 K	-	
Titania-based adsorbent							
Mesoporous TNTs	Hydrothermal	326	0.756	(15: 85 N ₂)/-	0.46 at 313 K	-	[27]
30wt% PEI-TNTs	Hydrothermal and wet impregnation	67	0.168	(15: 85 N ₂)/-	1.01 at 313 K	0.96 (10 th cycle)	
				(15:5 O ₂ :80 N ₂)/-	0.99 at 313 K	0.88 (10 th cycle)	
Clay-based adsorbent							
Porous Palygorskite	Hydration	137	0.32	(15 vol%: 80 vol% N ₂ : 5 vol% O ₂)/ 5 vol%	0.27 at 318 K	-	[28]
PEI-Palygorskite	Hydration and wet impregnation	0.11	0.11	(15 vol%: 80 vol% N ₂ : 5 vol% O ₂)/ 5 vol%	1.53 at 318 K	-	
Porous Sepiolite	Hydration	274	0.42	(15 vol%: 80 vol% N ₂ : 5 vol% O ₂)/ 5 vol%	0.925 at 318 K	-	

PEI-Sepiolite	Hydration and wet impregnation	-	-	(15 vol%: 80 vol% N ₂ : 5 vol% O ₂)/ 5 vol% N ₂ /-	1.270 at 318 K	1.10 (3rd cycle)	
Sepiolite	-	42.74	0.08	(60 vol%:40 vol% N ₂)/-	0.27 at 348 K	-	[29]
MgO-SiO ₂ Nanowire's sepiolite M Sep	Acid leaching	168.96	0.14	(60 vol%:40 vol% N ₂)/-	0.41 at 348 K	-	
50wt% PEI- M Sep	Acid leaching and wet impregnation	16.88	0.03	(60 vol%:40 vol% N ₂)/-	2.48 at 348 K	2.31 (10 th cycle)	
Carbon-based adsorbent							
Multi-walled CNTs	-	259.51	2.86	(15:85 N ₂)/- (15:5O ₂ :80 N ₂)/- (15:85 N ₂)/(RH=50%)	- - -	- - -	[30]
50wt%PEI-CNTs	Wet impregnation	33.67	0.33	(15:85 N ₂)/- (15:5O ₂ :80 N ₂)/- (15:85 N ₂)/(RH=50%)	4.75 at 333 K 4.42 at 333 K 4.97 at 333 K	4.5 (20 th cycle) - -	
Zeolite-based adsorbent							
Mesoporous ZSM-5	Hydrothermal	383.503	0.244	(99.99:0.01 N ₂)/-	0.4 at 393 K	-	[31]
30wt% PEI-ZSM-5	Hydrothermal and physical impregnation	6.066	0.027	(99.99:0.01 N ₂)/-	1.96 at 393 K	1.81 (10 th cycle)	
ZIF: Zeolitic imidazolate frameworks				MCM-41: Mobil Composition of Matter-41			
MCM-41: Mobil Composition of Matter-41				PCN-777: Polymers-loaded mesoporous metal organic framework			
TNTs: titanate nanotubes				MIL-101: Matériaux de l'Institut Lavoisier			
HMS-A: Hydrolysed mesoporous silica materials				CNTs: carbon nanotubes			
ZSM-5: Zeolite Socony Mobil-5				HMS-C: Calcined-HMS			
SFM: Siliceous foam materials							

2.1. Effect of amine loading

As previously mentioned, the PEI-impregnated approach could expressively improve the CO₂ adsorption capacity of numerous solid adsorbents. In general, the higher the amine loading will lead to increased CO₂ adsorption capacity. This is because the PEI incorporation could offer more additional active sites to ease the CO₂ adsorption of the solid adsorbents [32]. Based on table 1, Cheng et al. have conducted a study to investigate the effect of amine loading (20-60 wt.%) on Zn/Co zeolitic imidazolate frameworks (Zn/Co ZIF) adsorbents at pure CO₂ gas flow [20]. It was observed that the loading of 20% PEI has led to an increased CO₂ adsorption capacity from 1.07 mmol/g to 1.27 mmol/g and continuously increased up to 1.82 mmol/g for 40wt.%. However, when the PEI loading was further increased to 60 wt.%, the CO₂ uptake capacity was decreased to 1.35 mmol/g, most probably due to the superfluous amount of PEI that might block the main active sites of the adsorbent. Heo and co-workers also have reported the impregnation of PEI to titanate nanotubes (PEI-TNTs) that has successfully increased the CO₂ uptake capacity from 0.21 mg/g to 44.5 mg/g at 30 wt.% loadings. As expected, further addition of PEI to 40 wt.% has led to a decreased CO₂ uptake capacity. Based on both observations, it can be concluded that the excess amine content could suggestively reduce the CO₂ uptake capacity and adsorption rate of the PEI-modified adsorbents. These were due to the increase in CO₂ diffusion resistance caused by the presence of thicker PEI species at high amine loading [33]. The excess PEI loading also tends to block the pores and reduce the surface area and pore volume hence reduces the effective and active sites of the adsorbents [34]. Thus, it is important to recognize the optimum amine loading for that particular support to achieve the maximum CO₂ adsorption capacity.

2.2. Effect of the porous support

The pore structure of the support adsorbents undoubtedly plays an important impact in their CO₂ capture performances. Generally, the adsorbent that has large surface area and high microporosity are favorable for CO₂ adsorption [35]. In this regard, Henao et al. have studied the effect of pore structure of the support towards CO₂ adsorption performance of the hybrid adsorbents [12]. As reported in this study, the performance of the PEI-functionalization on the different porous and morphological structure of silica-based adsorbent were investigated. The morphological properties of studied mesoporous SBA-15, SBA-11 and SiO₂ were in 2D hexagonal, 3D cubic and disordered porous structure, respectively. Among those silica supports, it was perceived that the SBA-15 offered the highest surface area and pore volume. Due to these advantages, PEI-SBA-15 gave the highest CO₂ uptake (61.6 mg/g), followed by SBA-11 (32.9 mg/g) and SiO₂ (26.4 mg/g). The largest surface area and pore volume of SBA-15 undeniably have improved its CO₂ uptake performance [36], by providing a lower resistance for CO₂ diffusion [12, 37]. Meanwhile, the SBA-11 that has an interconnected three-dimensional porous system was reported to have the highest resistance for CO₂ diffusion. That clearly explained the reason for a lower CO₂ uptake capacity of PEI-SBA-11 than that of PEI-SBA-15 at the same PEI loading (40 wt.%). As result, the SiO₂ with a disordered structure has demonstrated the lowest CO₂ adsorption performance. Nevertheless, there is a study in table 1 that shows the large surface area support resulting in low CO₂ adsorption performance [28]. If we analyze the study by Gómez-Pozuelo and coworkers, in the beginning it was found out that the CO₂ adsorption uptake by pristine sepiolite adsorbents is high due to its greater surface area that is available for adsorption process. However, after impregnation with PEI, the CO₂ adsorption is still increasing but at a slower rate. This scenario happens because of the textural sepiolite that causes the blockage in the inner spores and reduces the number available active sites [28, 35]. Thus, it can conclude the type of support that needs to be selected should be favorable to be used with PEI for achieving high adsorption uptake capacity.

2.3. Effect of adsorption temperature

The other crucial factor that needs to be considered in the adsorption process is temperature. In general, the CO₂ adsorption could be reduced by the increase in temperature. Cheng et al have examined the CO₂ adsorption of 40wt.% PEI- Zn/Co ZIF at elevated temperatures from 25 °C to 90 °C [20]. The result has shown that the CO₂ adsorption has decreased gradually from 1.82 mmol/g (25 °C) to 1.24 mmol/g (90 °C).

However, some papers in table 1 reported in the increase in CO₂ adsorption performance at increasing temperatures for the PEI functionalized adsorbents [12, 22]. For example, Sanz-Pérez and co-workers have conducted a study on the effect of increasing temperature to 50wt.% PEI-hydrolysed mesoporous silica (PEI-HMS) at pure CO₂ adsorption flow [22]. The result demonstrated that the CO₂ uptake was considerably increased from 1.9 mmol/g at 30 °C to 4.19 mmol/g at 90 °C. Nevertheless, further increase in temperature to 105 °C has resulted in decreasing CO₂ uptake to 3.92 mmol/g. It was previously reported that the PEI becomes more flexible at the higher temperature, and thus more amino active sites were exposed [38]. As a result, the diffusion of CO₂ through the pore of the adsorbent becomes faster [39] and the CO₂ adsorption performance is increased. As the temperature exceeds the optimal temperature, the CO₂ adsorption then was controlled by the thermodynamics [40], at which all the amino sites were fully utilized [12, 41]. However, it is worth mentioning that the optimal temperature for each PEI-functionalized adsorbent is different based on their pristine structures. For instance, a study by Ouyang et al has reported that the CO₂ uptake of 50wt.% PEI-MgO-SiO₂ nanofibers sepiolite was at maximum capacity at 75°C [29]. While Henao and co-workers have described that 60 °C is the optimum temperature for a maximum capacity of 20wt.% PEI-mesoporous SBA-15 [12].

Interestingly, there is also a case in which the CO₂ uptake of PEI-magnesium oxide (PEI-MgO) based adsorbents are lower than the pristine MgO [42] but the performance was enhanced at higher temperature and exceed the CO₂ uptake of the pristine at 50 °C. This showed that the PEI-MgO is not capable of performing at low temperatures and it seems unusual behavior for the adsorption process. Thus, the type of adsorbent support that is selected is crucial based on their practical use which is either for low, medium, or high temperature.

2.4. Effect of different flow conditions toward adsorption performance

The flow conditions are one of other vital parameters that need to be observed. This is because the flue gas that was produced from the industry not only contains CO₂ but also contains other impurities. From table 1, there are several studies that are related to the difference of flow conditions towards CO₂ adsorption that conduct the presence of nitrogen gas (N₂) [18, 24], oxygen gas (O₂) [27, 30] and water (H₂O) [30]. Zhou and coworkers have studied the presence of N₂ in flow conditions as much of 12 volume percentage (12v%CO₂:88v%N₂) of PEI-Mobil Composition of Matter-550 (PEI-MCM-550) have reduced the adsorption performance from 2.32 mmol/g to 1.89 mmol/g. In addition, jeon et al have also conduct the comparison between the CO₂ adsorption of PEI-silica (Si) in pure CO₂ and 15% CO₂ with balance N₂, which have been observe the CO₂ uptake capacity in 15% CO₂ is lower (2.86 mmol/g) compared to pure CO₂ gas flow (3.20 mmol/g) at temperature of 353K. Hence, it can be said the drop concentration of CO₂ will reduce the CO₂ adsorption uptake capacity.

For the presence of O₂ in gas flow, Heo et al [27] have reported the presence of 5% O₂ in flue gas has no significant effect on the adsorption performance of PEI- titanate nanotubes (PEI-TNTs) during the first cycle. However, after the 10th cycle, the adsorption uptake capacity was reduced by 10% lower than the binary mixture in the presence of O₂. In addition, Wang et al, have observed the reduction of CO₂ adsorption capacity of PEI- PEI-multi-walled carbon nanotubes (PEI-CNTs) in the presence of 5% O₂ in flue gas from 4.75 mmol/g to 4.42 mmol/g [30]. This can be explained by the fact that the amino group of PEI-adsorbents is occupied and oxidized by O₂ that leads to the reducing number of available active sites for CO₂ diffusion, thus decreasing the CO₂ adsorption performance [30].

In contrast, the presence of water vapor has led to an increased CO₂ adsorption performance as compared to the binary mixture [43, 44]. For instance, Wang and co-workers [30] have achieved 4.42 mmol/g of CO₂ adsorption performance by using PEI-multi-walled carbon nanotubes (PEI-CNTs) under a humid gas mixture (15% CO₂, 85% N₂, RH = 50%), a slightly higher CO₂ uptake than that of performed under 15% CO₂, 5% O₂ and 80% N₂ condition (4.22 mmol/g) [30]. It is believed that the enhanced CO₂ adsorption performance is due to the formation of carbamate and bicarbonate in the humid environment, in which the only carbamate is formed in dry conditions [45]. The formation of bicarbonate requires lower amino compared to carbamate during the dry conditions. However, too high amounts of water will cause competition with CO₂ in occupying the active sites of amino [46].

2.5. Effect of crosslinking

One of the problems that countered in the most PEI support technology is the formation of urea during the regeneration process at high contain of CO₂ and high temperature. [47]. The formation of urea has often been produced from the reaction of primary amines and CO₂. This will cause the large drop of CO₂ adsorption uptake at high Adsorption cycle. To overcome these problems jeon et al have studied the effect of modified crosslinking PEI toward the CO₂ adsorption. The modification of crosslinking PEI lead to increasing the surface area but it caused the reduction in the amount of PEI contain. This

can be shown as the CO₂ uptake for PEI-Si is 2.86 mmol/g at 353 K and influence of 85% N₂ whereas the crosslinking PEI-silica (PEI-Si) is 2.06 mmol/g. Hence, it shown the crosslinking contain less amino active sites compared to pristine PEI. Unexpectedly after the 40th cycle, the crosslinking PEI-Si can maintain the greater CO₂ adsorption capacity which is about 61% of its highest value. This performance showed a lot of improvement of chemical stability as compared to the pristine PEI (16.9%). The improvement of chemical stability is due to cross-linkers shape capable of reducing the urea formation by lesser contact of primary amine and CO₂. Thus, reducing the formation of urea. It was also observed that crosslinking PEI with greater alkyl chains shows a lower formation of urea and greater chemical stability.

3. Conclusions

In this work, the recent studies on the PEI impregnated adsorbents for enhanced CO₂ capture have been thoroughly discussed. The summary effects of each parameter on CO₂ adsorption as in Table 2. It is vital to evaluate each parameter in order to achieve effective CO₂ capture technology. It can be concluded that the growing numbers of recent studies on PEI impregnated on various types of adsorbents has been proved could significantly assist to determine the most effective performance and cost for practical applications of CO₂ capture.

Table 2. The summarize the effect of parameters on CO₂ adsorption

Parameters	Effect on CO ₂ adsorption
Amine loading	<ul style="list-style-type: none"> ● Achieve maximum CO₂ adsorption capacity at optimum amine loading for those capable of that support. ● Too high amount of amine loading will cause a decrease in CO₂ adsorption uptake.
Porous support	<ul style="list-style-type: none"> ● The porous support with better morphological structure tends to perform better in CO₂ adsorption.
Adsorption temperature	<ul style="list-style-type: none"> ● PEI support achieves maximum CO₂ adsorption when it reaches its optimum temperature that depends on their support.
Flow conditions	<ul style="list-style-type: none"> ● Presence of N₂ and O₂ in flow conditions causes negative effects since it causes reduction of the number of amino active sites. ● Presence of H₂O in flow conditions causing positive effect due to formation of bicarbonate.
Crosslinking PEI	<ul style="list-style-type: none"> ● This modification causes a drop in CO₂ adsorption uptake capacity but increases the chemical stability of PEI-support.

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References

- [1] Shukla JB, Verma M, Misra AK. 2017 Effect of global warming on sea level rise: A modeling study *Ecological Complexity* **32** 99-110.
- [2] Kurane I. 2010 The effect of global warming on infectious diseases *Osong Public Health Res Perspect* **1**(1) 4-9.
- [3] Yoro KO, Daramola MO. Chapter 1 - CO₂ emission sources, greenhouse gases, and the global warming effect. In: Rahimpour MR, Farsi M, Makarem MA, editors. *Advances in Carbon Capture*: Woodhead Publishing; 2020. p. 3-28.
- [4] Peridas G, Mordick Schmidt B. 2021 The role of carbon capture and storage in the race to carbon neutrality *The Electricity Journal* **34**(7) 106996.

- [5] Yan J, Zhang Z. 2019 Carbon Capture, Utilization and Storage (CCUS) *Applied Energy* **235** 1289-99.
- [6] Yuan Y, You H, Ricardez Sandoval LA. 2019 Recent advances on first-principles modeling for the design of materials in CO₂ capture technologies *Chin J Chem Eng* **27(7)** 1554-1565.
- [7] Spigarelli BP, Kawatra SK. 2013 Opportunities and challenges in carbon dioxide capture *Journal of CO₂ Utilization* **1** 69-87.
- [8] Zhang J-p, Zuo J, Ai W, Zhang J, Zhu D, Miao S, et al. 2021 Preparation of mesoporous coal-gasification fine slag adsorbent via amine modification and applications in CO₂ capture *Appl Surf Sci* **537** 147938.
- [9] Hosseini Y, Najafi M, Khalili S, Jahanshahi M, Peyravi M. 2021 Assembly of amine-functionalized graphene oxide for efficient and selective adsorption of CO₂ *Mater Chem Phys* **270** 124788.
- [10] Meng Y, Jiang J, Gao Y, Yan F, Liu N, Aihemaiti A. 2018 Comprehensive study of CO₂ capture performance under a wide temperature range using polyethyleneimine-modified adsorbents *Journal of CO₂ Utilization* **27** 89-98.
- [11] Zhang Y, Chen M, Li G, Shi C, Wang B, Ling Z. 2020 Exfoliated vermiculite nanosheets supporting tetraethylenepentamine for CO₂ capture *Results in Materials* **7** 100102.
- [12] Henao W, Jaramillo LY, López D, Romero-Sáez M, Buitrago-Sierra R. 2020 Insights into the CO₂ capture over amine-functionalized mesoporous silica adsorbents derived from rice husk ash *J Environ Chem Eng* **8(5)** 104362.
- [13] Fatima SS, Borhan A, Ayoub M, Ghani NA. 2021 Development and progress of functionalized silica-based adsorbents for CO₂ capture *J Mol Liq* **338** 116913.
- [14] Jiang F, Zhao W, Wu Y, Wu Y, Liu G, Dong J, et al. 2019 A polyethyleneimine-grafted graphene oxide hybrid nanomaterial: Synthesis and anti-corrosion applications *Appl Surf Sci* **479** 963-73.
- [15] Alkadhém AM, Elgzoly MAA, Onaizi SA. 2020 Novel Amine-Functionalized Magnesium Oxide Adsorbents for CO₂ Capture at Ambient Conditions *J Environ Chem Eng* **8(4)** 103968.
- [16] Gaikwad S, Kim Y, Gaikwad R, Han S. 2021 Enhanced CO₂ capture capacity of amine-functionalized MOF-177 metal organic framework *J Environ Chem Eng* **9(4)** 105523.
- [17] Gaikwad S, Kim S-J, Han S. 2019 CO₂ capture using amine-functionalized bimetallic MIL-101 MOFs and their stability on exposure to humid air and acid gases *Microporous Mesoporous Mater* **277** 253-60.
- [18] Jeon S, Min J, Kim SH, Lee KB. 2020 Introduction of cross-linking agents to enhance the performance and chemical stability of polyethyleneimine-impregnated CO₂ adsorbents: Effect of different alkyl chain lengths *Chem Eng J* **398** 125531.
- [19] Park JM, Jhung SH. 2020 CO₂ adsorption at low pressure over polymers-loaded mesoporous metal organic framework PCN-777: effect of basic site and porosity on adsorption *Journal of CO₂ Utilization* **42** 101332.
- [20] Cheng J, Liu N, Hu L, Li Y, Wang Y, Zhou J. 2019 Polyethyleneimine entwine thermally-treated Zn/Co zeolitic imidazolate frameworks to enhance CO₂ adsorption *Chem Eng J* **364** 530-40.
- [21] Mutyala S, Jonnalagadda M, Mitta H, Gundeboyina R. 2019 CO₂ capture and adsorption kinetic study of amine-modified MIL-101 (Cr) *Chem Eng Res Des* **143** 241-8.
- [22] Sanz-Pérez ES, Arencibia A, Calleja G, Sanz R. 2018 Tuning the textural properties of HMS mesoporous silica. Functionalization towards CO₂ adsorption *Microporous Mesoporous Mater* **260** 235-44.
- [23] Meng Y, Yan Y, Wu X, Sharmin N, Zhao H, Lester E, et al. 2020 Synthesis and functionalization of cauliflower-like mesoporous siliceous foam materials from oil shale waste for post-combustion carbon capture *Journal of CO₂ Utilization* **40** 101199.
- [24] Zhou C, Yu S, Ma K, Liang B, Tang S, Liu C, et al. 2021 Amine-functionalized mesoporous monolithic adsorbents for post-combustion carbon dioxide capture *Chem Eng J* **413** 127675.
- [25] Ojeda M, Mazaj M, Garcia S, Xuan J, Maroto-Valer MM, Logar NZ. 2017 Novel Amine-impregnated Mesostructured Silica Materials for CO₂ Capture *Energy Procedia* **114** 2252-8.
- [26] Ahmed S, Ramli A, Yusup S. 2017 Development of polyethyleneimine-functionalized mesoporous

- Si-MCM-41 for CO₂ adsorption *Fuel Process Technol* **167** 622-30.
- [27] Heo Y-J, Seong DB, Park S. 2019 Synthesis of polyethylenimine-impregnated titanate nanotubes for CO₂ capture: Influence of porosity and nitrogen content on amine-modified adsorbents *Journal of CO₂ Utilization* **34** 472-8.
- [28] Gómez-Pozuelo G, Sanz-Pérez ES, Arencibia A, Pizarro P, Sanz R, Serrano DP. 2019 CO₂ adsorption on amine-functionalized clays *Microporous Mesoporous Mater* **282** 38-47.
- [29] Ouyang J, Gu W, Zheng C, Yang H, Zhang X, Jin Y, et al. 2018 Polyethyleneimine (PEI) loaded MgO-SiO₂ nanofibers from sepiolite minerals for reusable CO₂ capture/release applications *Applied Clay Science* **152** 267-75.
- [30] Wang Y, Hu X, Guo T, Tian W, Hao J, Guo Q. 2021 The competitive adsorption mechanism of CO₂, H₂O and O₂ on a solid amine adsorbent *Chem Eng J* **416** 129007.
- [31] Wang Y, Du T, Qiu Z, Song Y, Che S, Fang X. 2018 CO₂ adsorption on polyethylenimine-modified ZSM-5 zeolite synthesized from rice husk ash *Mater Chem Phys* **207** 105-13.
- [32] Lou F, Zhang A, Zhang G, Ren L, Guo X, Song C. 2020 Enhanced kinetics for CO₂ sorption in amine-functionalized mesoporous silica nanosphere with inverted cone-shaped pore structure *Applied Energy* **264** 114637.
- [33] Liu F, Chen S, Gao Y. 2017 Synthesis of porous polymer based solid amine adsorbent: Effect of pore size and amine loading on CO₂ adsorption *J Colloid Interface Sci* **506** 236-44.
- [34] Guo X, Ding L, Kanamori K, Nakanishi K, Yang H. 2017 Functionalization of hierarchically porous silica monoliths with polyethyleneimine (PEI) for CO₂ adsorption *Microporous Mesoporous Mater* **245** 51-7.
- [35] Cecilia JA, Vilarrasa-García E, Cavalcante CL, Azevedo DCS, Franco F, Rodríguez-Castellón E. 2018 Evaluation of two fibrous clay minerals (sepiolite and palygorskite) for CO₂ Capture *J Environ Chem Eng* **6**(4) 4573-87.
- [36] Ullah R, Atilhan M, Aparicio S, Canlier A, Yavuz CT. 2015 Insights of CO₂ adsorption performance of amine impregnated mesoporous silica (SBA-15) at wide range pressure and temperature conditions *International Journal of Greenhouse Gas Control* **43** 22-32.
- [37] Jahandar Lashaki M, Sayari A. 2018 CO₂ capture using triamine-grafted SBA-15: The impact of the support pore structure *Chem Eng J* **334** 1260-9.
- [38] Zhao P, Zhang G, Sun Y, Xu Y. 2017 CO₂ Adsorption Behavior and Kinetics on Amine-Functionalized Composites Silica with Trimodal Nanoporous Structure *Energy & Fuels* **31**(11) 12508-20.
- [39] Wu J, Zhu X, Yang F, Ge T, Wang R. 2021 Easily-synthesized and low-cost amine-functionalized silica sol-coated structured adsorbents for CO₂ capture *Chem Eng J* **425** 131409.
- [40] Liu F, Huang K, Yoo C-J, Okonkwo C, Tao D-J, Jones CW, et al. 2017 Facilely synthesized meso-macroporous polymer as support of poly(ethyleneimine) for highly efficient and selective capture of CO₂ *Chem Eng J* **314** 466-76.
- [41] Chen C, Son W-J, You K-S, Ahn J-W, Ahn W-S. 2010 Carbon dioxide capture using amine-impregnated HMS having textural mesoporosity *Chem Eng J* **161**(1) 46-52.
- [42] Alkadhém AM, Elgzoly MAA, Alshami AS, Onaizi SA. 2021 Kinetics of CO₂ capture by novel amine-functionalized magnesium oxide adsorbents *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **616** 126258.
- [43] Lai Q, Diao Z, Kong L, Adidharma H, Fan M. 2018 Amine-impregnated silicic acid composite as an efficient adsorbent for CO₂ capture *Applied Energy* **223** 293-301.
- [44] Johnson O, Joseph B, Kuhn JN. 2021 CO₂ separation from biogas using PEI-modified crosslinked polymethacrylate resin sorbent *Journal of Industrial and Engineering Chemistry* **103** 255-63.
- [45] Wang Y, Guo T, Hu X, Hao J, Guo Q. 2020 Mechanism and kinetics of CO₂ adsorption for TEPA-impregnated hierarchical mesoporous carbon in the presence of water vapor *Powder Technol* **368** 227-36.
- [46] Irani M, Jacobson AT, Gasem KAM, Fan M. 2017 Modified carbon nanotubes/tetraethylenepentamine for CO₂ capture *Fuel* **206** 10-8.

- [47] Jung H, Jeon S, Jo DH, Huh J, Kim SH. 2017 Effect of crosslinking on the CO₂ adsorption of polyethyleneimine-impregnated sorbents *Chem Eng J* **307** 836-44.