Recent progress on (3-Aminopropyl)triethoxysilane (APTES) functionalized-adsorbent for CO_2 capture

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Abstract. The increasing emission of carbon dioxide (CO_2) to the atmosphere has gained worldwide concern due to its main contribution to climate changes, global warming, and the greenhouse effect. Numbers of technologies have been carried out to remove this hazardous gas from the environment such as absorption, adsorption, membrane separation, cryogenic separation, and the biological process. Due to limitation of the current absorption technique, CO_2 adsorption technique using porous solid adsorbents seems to be a potential candidate in capturing CO_2. This is due to the advantages such as low regeneration energy requirements, no liquid waste and low cost. Furthermore, amine functionalization such as APTES on solid adsorbents has been progressively study for the usage of enhancing CO_2 adsorption. The uses of adsorbents that modified with APTES could enhance the CO_2 adsorption performance due to the chemisorption of $-NH_2$ bond from the amine that further improve the CO_2 adsorption performance in terms of the CO_2 uptake and selectivity. Besides that, functionalization of APTES on adsorbent will also greatly enhance the reactivity towards CO_2. In this review, the impact of the diverse amine loadings on different adsorbents and the type of solvent used for APTES-functionalization towards CO_2 capture performance was thoroughly elaborated. The suitable reaction conditions and the regenerability of the adsorbents that could significantly affect their CO_2 adsorption capacity were also discussed in detail. Other than distributing useful knowledge on the current progress of the APTES-functionalization adsorbents, this review is anticipated to provide benefit for the industrial and academic usage and appeal more attention in this fascinating area of CO_2 capture.

1. Introduction

CO_2 has become a major worldwide concern due to its adverse impacts on human health and the environment. Numerous human activities such as the combustion of oil, coal, and gas, as well as deforestation, have significantly raised the CO_2 concentrations in the atmosphere since the Industrial Revolution. Although the combustion of fossil fuels is the most significant source of CO_2 emissions, the presence of this gas in the atmosphere might also be contributed by natural sources such as the breathing of animals, volcanic eruptions, and the release of CO_2 from the ocean. CO_2 as one of the greenhouse gases and global warming contributors inevitably cause numerous human and environmental problems. This includes the melting of polar ice caps, economic implications, warmer oceans, and more hurricanes, disease transmission, and earthquakes. In this respect, there is the need for the development of new technologies to capture CO_2 and minimize its emission levels for the continuous development of human civilization. Various CO_2 capture techniques were considered such as cryogenic distillation, absorption

into a liquid, adsorption on a solid, as well as membrane separation. Even the chemical absorption is widely used, this method suffers from several drawbacks such as low CO_2 uptake capacity, high equipment corrosion rate, amine degradation by sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and oxygen (O_2) in the flue gases which induce the high absorbent makeup rate, and high energy consumption during high-temperature absorbent regeneration [1].

Currently, carbon capture via chemical (amines) absorption technique is the common industrial used method. However, several drawbacks related to amine utilization such as high energy consumption during the regeneration process, corrosive nature, etc. have restricted its widespread applications [2]. The previous studies have revealed that this issue could be reduced via the incorporation of various solid adsorbents [3]. Also, the amine-functionalization of solid adsorbent has become a promising carbon capture approach nowadays. The addition of $-NH_2$ from the amine to the adsorbent with the existing Lewis and Bronsted acid site will further improve the CO_2 adsorption performance in terms of the CO_2 uptake and selectivity. There are extensive studies that have been reported associated with amine (e.g. (3-aminopropyl) triethoxysilane (APTES)) functionalized on numerous solid adsorbents such as metal oxides (e.g. MgO) [4], zeolites [5], SBA-15 silica [6], MOFs, etc. As one of the potential amines, APTES-functionalization was usually achieved via the grafting method. The APTES shows significant interaction with the adsorbent due to the presence of silylating moieties, which allow the covalent bonding between APTES and adsorbents [6]. Owing to these features, APTES has been progressively studied in gaining high uptake capacity and stability of solid adsorbent. The critical characteristics of CO_2 adsorbents include porous morphology, high specific surface area, and the amount and nature of chemical modifications [7]. Moreover, as compared to unmodified materials, amine-functionalized nanomaterials have shown increased CO_2 capacity. Due to their tunability and reduced heat capacity compared to liquid amine solutions, amine-functionalized solid adsorbents are considered attractive materials for CO_2 capture. Besides, the supported amine materials are most commonly used in temperature swing adsorption (TSA) processes or similar cyclic processes, in which adsorption occurs at low temperatures and desorption is triggered by heating the adsorbent [8]. The early reported studies have verified that the primary methodologies for the synthesis of amine-modified nanomaterials are wet impregnation and grafting on porous materials.

To the best of our knowledge, a review on the use of APTES functionalized numerous adsorbents for CO_2 capture is still in infancy. By considering that the increasing numbers of research works have been dedicated on this subject, this review was conducted to provide the latest review focusing on APTES functionalization of different types of adsorbents for improved CO_2 uptake from the atmosphere, which might be beneficial for industrial and academic usage.

2. Discussion

In this paper, several aspects regarding the effect of APTES functionalized adsorbents, diverse synthesis parameters, and the impact of several adsorption conditions towards CO_2 adsorption capacity were thoroughly elaborated. Finally, the regeneration ability of amine-functionalized adsorbents was briefly investigated to further highlight the additional advantages of these modified adsorbents.

2.1 APTES Functionalization on Solid Adsorbent

Many studies have been conducted on the APTES functionalization of different adsorbents as summarized in Table 1. For instance, Alkadhem and co-workers have reported on the APTES functionalization of the porous MgO as anchor support [4]. It was found that the irregular pure platelet-like MgO has demonstrated the CO_2 adsorption capacity of 0.68 mmol/g. Meanwhile, the solvent-assisted grafting of APTES on MgO has enhanced the CO_2 adsorption to 1.49 mmol/g. These results can be related to their morphological structures, in which the pure MgO has well-defined mesopores, whereas APTES-MgO adsorbents have non-rigid aggregates of slit-shaped porous materials with a broad pore size range. Because of the difference in the textural characteristics, each adsorbent has a varied adsorption capacity and large surface areas are generally linked with a high capacity for CO_2 adsorption. However, the effect of another parameter which is the enhancement of chemical properties

due to the addition of surface functional group (e.g, amine) on the adsorbent, may be more significant than its surface area. As a result, a considerable reduction in the surface area of MgO was perceived due to the APTES functionalization together with a subsequent dramatic enhancement in CO_2 adsorption capability. As demonstrated in Table 1, the surface area and pore volume of the modified adsorbents were reduced after the incorporation of amine molecules that intercalating between the MgO layers. These can be explained by the fact that the amine molecules were connected to MgO by filling in some pores, particularly the tiny pore of the mesoporous materials. Despite the reduction in the surface area and pore volume of MgO upon its functionalization with APTES, it could be seen that its pore size has significantly expanded due to amine attachment and intercalation between the MgO layers. A similar improvement of CO_2 uptake capacity upon the APTES functionalization approach was also being reported by other studies (Table 1).

Table 1. Summary of Amine-functionalized and raw adsorbents in CO_2 adsorption application.

Synthesis Method	Adsorbent	BET surface area (m²/g)	BJH pore volume (cm³/g)	Temperature (K)	Adsorption flow condition (CO₂%: inert gas%)/% H₂O	CO₂ uptake (mmol/g)	Stability (mmol/g)	Ref.
Sol-gel method	MgO	350 ± 7	0.414	303	(99.9:0)/-	0.68	-	[4]
Sol-gel+ Solvent-assisted grafting method	APTES-MgO	134 ± 2	0.301	303	(99.9:0)/-	1.49	1.39 (6th cycle)	
-	MPS	300	1.15	373	(15:85)/-	-	-	[9]
Wet impregnation method	APTES-MPS	-	-	373	(15:85)/-	1.82	2.09 (10th cycle)	
Phase inversion induced sol-gel	Cellulose Aerogel	-	-	298	(1:99)/-	0.15	-	[10]
Phase inversion induced sol-gel + Grafting method	APTES + Cellulose Aerogel	-	-	298	(1:99)/-	1.20	1.4 (20th cycle)	
Extraction from catalytic gasification coal ash	AR	665.19	0.82	298	(100:0)/-	-	-	[11]
Extraction from catalytic gasification coal ash + Grafting method	APTES-AR	151.73	0.26	298	(100:0)/-	1.23	0.99 (5th cycle)	
Pore expansion	MCM-41	1007	0.94	298	(15:85 N₂)/-	0.63	-	[12]
	SBA-15	737	1.24	298	(15:85 N₂)/-	0.71	-	
	KIT-6	672	0.99	298	(15:85 N₂)/-	0.52	-	
Pore expansion + Grafting method	APTES-MCM-41	58.1	0.12	298	(15:85 N₂)/-	1.01	0.95 (5th cycle)	
	APTES-SBA-15	20.1	0.13	298	(15:85 N₂)/-	1.75	1.55 (5th cycle)	
	APTES-KIT-6	16.2	0.09	298	(15:85 N₂)/-	1.30	1.11 (5th cycle)	
Improved Tour's method	GO	-	-	303	(100:0)/-	1.1	-	[13]
Solvothermal method	ZIF-8	-	-	303	(100:0)/-	0.65[a]	-	
		-	-	303	(100:0)/H₂O	0.65[a]	-	
In situ nucleation method	ZIF-8/GO	-	-	303	(100:0)/-	0.45	-	
Improved Tour's + Grafting method	APTES-GO	-	-	303	(100:0)/-	1.50	-	
		-	-	303	(100:0)/H₂O	1.95	-	
		-	-	303	(100:0)/-	0.82[a]	-	

Method	Material							Ref
Solvothermal + Functionalised method	APTES-ZIF-8	-	-	303	(100:0)/H_2O	0.82[a]	-	
Solvothermal + Post-functionalised method	APTES-ZIF-8/GO	-	-	303	(100:0)/-	0.21	-	
		-	-	303	(100:0)/H_2O	0.50	-	
Hydrothermal method	CSNS1.5	69.18	0.2092	298	(100:0)/-	0.44[b]	-	[14]
	CSNS3	141.68	0.4222	298	(100:0)/-	0.56[b]	-	
	CSNS10	270.29	0.7305	298	(100:0)/-	0.47[b]	-	
Hydrothermal + Chemical grafting method	APTES-CSNS1.5	7.46	0.09	298	(100:0)/-	0.63[b]	0.77 (20th cycles)	
	APTES-CSNS3	18.25	0.19	298	(100:0)/-	0.69[b]	-	
	APTES-CSNS10	33.05	0.29	298	(100:0)/-	0.81[b]	-	
Sol-gel method	SBA	572	0.9	303	(100:0 HE)/-	0.59	-	[6]
Sol-gel + Grafting method	APTES-SBA-AE	276	0.5	303	(100:0 HE)/-	0.84	-	
Sol-gel + Grafting method	APTES-SBA-TE	50	0.1	303	(100:0 HE)/-	1.43	-	
-	AC	52.5	0.008	298	(100:0)/-	3.84	-	[15]
Impregnation method	APTES-AC (DI Water)	74.7	0.023	298	(100:0)/-	55.40	-	
	APTES-AC (Ethanol)	78.0	0.016	298	(100:0)/-	172.73	-	
-	FS	289	0.72	348	(100:0)/-	0.15	-	[16]
Wet impregnation method	APTES-FS	187	1.09	348	(100:0)/-	0.61	-	
Hydrothermal method	MCFs	824	1.213	298	(100:0)/-	1.13	-	[17]
Hydrothermal + Grafting method	APTES-MCF	197	-	298	(100:0)/-	1.11	-	
		247	-	353	(100:0)/-	1.45	-	
Hydrothermal method	Silicas	610	1.49	348	(15:85)/-	0.10	-	[18]
Hydrothermal + Grafting method	APTES-Silica	-	-	298	(15:85)/-	0.58[b]	0.75 (20th cycle)	
		-	-	333	(15:85)/-	0.49[b]	-	
		194	0.86	348	(15:85)/-	0.43[b]	0.42 (20th cycle)	
Ball drop method	SSA	541.040	1.4830	308	(1:99)/-	-	-	[19]
Ball drop + Grafting method	APTES-SSA-3	203.586	0.4883	308	(1:99)/-	1.56	0.92 (10th cycle)	

[a] CO_2 uptake capacity under 0.95 atm
[b] CO_2 uptake capacity under 0.15 atm

APTES	: 3-aminopropyltriethoxysilane
MgO	: Magnesium oxide
AR	: Alumina-extracted residue
MCM-41	: Mesoporous silica with hexagonal structure
SBA-15	: Mesoporous silica-15
KIT-6	: Mesoporous silicas with cubical interconnected pore structure
GO	: Graphite oxide
ZIF-8	: Zeolitic imidazolate framework
CSNSs	: Copper silicate nanospheres
MCF	: Mesoporous silica foams
APTES-SBA-TE	: SBA + APTES + Toluene
APTES-SBA-AE	: SBA + APTES + Ethanol
FS	: Fumed silica
SSA	: Spherical silica aerogel

In addition, different synthesis times for the reaction between adsorbent and amine also could suggestively affect the adsorption capacity. From the study by Ren et al., it was observed that the use of different hydrothermal reaction times for the synthesis of amine functionalized-copper silicate nanospheres (CSCNs) has resulted in different CO_2 uptake capabilities [14]. Herein, the pore volumes and specific surface areas of the CSNSs rose with the increase of hydrothermal durations, while the average pore diameters did not change dramatically. From the table, it could be seen that after APTES functionalization, the average pore diameter of the adsorbents increased, while the pore volume was considerably lower than that of the CSNS samples. With the introduction of the functional amine groups into the CSNS pores, the supplied amines filled part of the layered pores in the CSNS (1.0 – 3.0 nm) and raise the average size of the pore. Furthermore, the specific surface areas of the modified CSNSs were reduced compared to those of the unaltered CSNSs due to blockages of micropores by the APTES molecules. It could be summarized that the expansion of adsorbent's pores upon APTES grafting has resulted in the increase of CO_2 capture for CSNS1.5, CSNS3.0, and CSNS10 from 0.44, 0.56, 0.47mmol/g to 0.63, 0.69, and 0.81mmol/g, respectively.

Furthermore, the amount of amine loading also could significantly impact the CO_2 adsorption of the adsorbents. For instance, a study was conducted by Wang and co-workers on CO_2 capture of fumed silica (FS) with no definite structure and tiny mesopores particles that might suffer an agglomeration issue [16]. As APTES covers the surface of silica support, the total pore volume and surface area were declined progressively, but still significantly higher than that of the pure FS. This shows that the addition of APTES has reinforced the aggregation and generates more pores for an additional amount of pore volume of the FS. The bare FS support has shown a low CO_2 sorption capacity of 0.15 mmol/g, however with the addition of 9 wt % APTES, even the pore volume had been greatly enlarged, its sorption capacity for CO_2 was almost the same as the FS alone. With the increase of APTES content, the CO_2 capacity increased to 0.2, 0.37, and 0.61 mmol/g for 17APTES-FS, 23APTES-FS, and 30APTES-FS, respectively. On the other hand, Jiang et al. have also conducted a study on the different amine loading times which also affect the CO_2 capture capacity [10]. It was observed that with increasing in grafting times, the CO_2 adsorption capacity was first increases, then begins to decline at certain times. Although longer grafting times may result in higher amine loading according to the TG curves, the APTES-SASA-3 had the greatest CO_2 adsorption capacity of 1.56 mmol/g. The surface content of the amine relies on the loading of amines and the particular surface area. However, the excessive loading of amines has caused a decrease in specified surface area when numerous amine groups are coated. Overall, the amine surface content of the grafting process was regulated by the particular surface area and amine loading. The longer grafting time has led to pore blockage and the amine group's coverage, therefore resulting in a reduction in the CO_2 uptake capacity.

2.2 The influence of amine functionalization synthesis parameter

Other than the above-mentioned factors, the synthesis conditions during the amine grafting procedure also have significant impacts on the CO_2 adsorption performance. It is widely known that the solvent used to dissolve these groups could expressively impact the grafting process. In one of the related studies, the grafting of amines onto SBA-15 by utilizing various solvents such as toluene and ethanol was investigated [6]. It was demonstrated that the integration of APTES into the silica structure has resulted in the reduction in surface area, due to the blocking of pores by APTES. The smaller surface area of SBA-AT compared to SBA-AE may be attributed to a higher level of pore blockage in this material. In addition, the amine concentration in SBA-AT and SBA-AE were estimated at 2.40±0.10 and 1.20±0.05 mmol/g, respectively. Thus, a higher concentration of APTES in SBA-AT than SBA-AE indicated the significant blockage of pores in the structure of this adsorbent. The CO_2 uptake tests pointed out that SBA-AT showed the highest uptake capacity (1.43 mmol/g), followed by SBA-AE (0.84 mmol/g) and SBA (0.59 mmol/g). This result evidencing that the increase in amine loading has diminished the particular surface area of the materials, which consequently relates to the adsorptive behavior. Overall, the SBA-AT possesses the optimal combination between amines loading and surface area at 30°C and atmospheric pressure for excellent CO_2 adsorption.

On top of that, Saaroni et al. have also carried out a research using different solvent for amine functionalization [15]. It was found that the CO_2 adsorption capacity for raw AC was 169 mg/g and the adsorption capacity increased after loading the APTES to the AC using deionized (DI) water and ethanol. This suggests that the addition of APTES to the AC has enhanced the CO_2 adsorption due to the presence of amine groups. The highest CO_2 adsorption capacity was observed in this investigation at 4wt% and 5wt% APTES loadings, which were 14 times and 45 times the CO_2 adsorption capacity of raw AC when utilizing DI water and ethanol as solvent, respectively. Nonetheless, increasing the APTES load from 4wt% to 5wt% causes a substantial reduction in CO_2 adsorption capability when DI water is used as a solvent. This might be due to the reduction of the adsorbent's micropores volume, which is responsible for CO_2 physisorption. The excessive APTES deposition may result in polymerized APTES products that partially block the AC micropores. It is also discovered that combining APTES-AC with ethanol as a solvent could considerably improve the CO_2 adsorption capacity when compared to using DI water as a solvent. This can be explained due to the acceleration of the APTES ethoxy group's hydrolysis by water to create a polymer comprised of polysiloxane and to prevent the APTES binding with the AC surface. Whereas ethanol solvent possesses a nucleophilic attack on APTES amine groups, which increases the amine group attached to the AC surface.

2.3   The effect of CO_2 adsorption condition on amine-functionalized capture performance.
Following structural and morphological evaluation, the resulting adsorbents under the presence of pre-adsorbed water can be evaluated as well. When compared to unmodified graphene oxide (GO), the use of APTES-GO has resulted in a 36% increase in adsorption capacity at 1 bar and 303K, and a further 33% increase was perceived in the presence of pre-adsorbed water (10% RH) compared to the corresponding APTES-GO capacity under dry circumstances. In another study, amine functionalization of ZIF-8 has increased the CO_2 adsorption capacity by up to 43 % at 1 bar compared to unmodified ZIF-8. Meanwhile, ZIF-8/GO post-functionalization in water has increased the CO_2 uptake capacity of this composite adsorbent as compared to the non-functionalized ZIF-8/GO and pure ZIF-8, particularly at lower pressures [13]. In the case of APTES-GO adsorbent, it was proved that at high relative humidity (RH), the pre-adsorbed water acts beneficially to the CO_2 adsorptivity on pristine GO. At greater RH, a wedge opening of the stacked flakes may cause this enhancement. Theoretical investigations have recently revealed that when water molecules contact the oxygen-containing groups of GO layers, the stacks are wedged open, allowing the pristine part of the GO layers to be exposed. Water molecules that enter this pristine graphene fraction of a layer are quickly pushed out to bulk or oxidized regions due to a minimal change in free energy, resulting in rapid penetration channels. In this instance, the accessibility of CO_2 to the GOs interlayer region is regained at high RH levels. Hence, the adsorption capacity of CO_2 in wet conditions will be higher than in dry conditions which are 1.95 mmol/g and 1.50 mmol/g respectively.

In comparison to the GO samples, the amine contact with the surface of the functionalized ZIF-8 is a physical interaction, as opposed to the GO samples, where greater binding occurs. The moisture effect was minimal for all adsorbents, resulting in a 1–2 % reduction in adsorptivity as compared to dry conditions [13]. Additionally, the CO_2 adsorption capability of the APTES-(ZIF-8/GO)-water composite (0.50 mmol/g) surpasses that of non-functionalized ZIF-8/GO (0.20 mmol/g). However, its performance remains modest when compared to APTES-ZIF-8, suggesting that simple functionalization of APTES-ZIF-8 (0.82 mmol/g) leads to a more efficient CO_2 adsorbent in terms of capacity when compared to ZIF-8/GO adsorbents at the current preparation circumstances. The preparation method of the APTES-(ZIF-8/GO) composite has resulted in a full GO exfoliation, thus reduces the CO_2 uptake capacity due to the loss of the highly-adsorbing GO stacking structure. Furthermore, the pre-functionalization of ZIF-8/GO has impacted the crystalline quality of the generated ZIF-8, leading to a decrease in CO_2 adsorption capacity. However, as compared to both non-functionalized ZIF-8/GOs, the post-functionalization in water has increased the capacity of the APTES-ZIF-8/GO.

Furthermore, Gracia et al. have investigated various mesoporous silica foams produced by changing the aging temperature, resulting in greater pore diameter materials [17]. As the aging temperature rises,

the specific surface area decreases. The rise in aging temperature induces a change in the average pore size to larger values. The distribution, on the other hand, is wide, indicating the creation of a rather diverse structure. According to the adsorption results, the adsorbent produced at room temperature (MCF-RT) had the maximum CO_2 adsorption capacity, with a value of 1.13 mmol/g at 298K and 100 kPa (0.98 atm). Also, the aging temperature induces a gradual decrease in CO_2 adsorption, with MCF-140 achieving the lowest value of 0.55 mmol/g under identical testing circumstances. This tendency is related to the textural characteristics of the MCFs since it is widely known that porous materials function as sieves in CO_2 selective adsorption. As a result, materials with smaller pore sizes and narrower pore size distributions achieve the greatest CO_2 uptakes. The CO_2 uptakes for APTES-MCF adsorbents, on the other hand, do not follow the same patterns as those reported for non-functionalized silica samples. In the case of the APTES-MCFs, the highest CO_2 adsorption capacity was obtained for the sample APTES-MCF-80, which reaches a value of 1.45 mmol/g CO_2 at 100 kPa and 298K, while adsorbents with narrower pore size, such as MCF-RT, only reaches 1.11 mmol/g CO_2. This is due to the expansion of the pore size due to greater aging temperatures. However, for the aging temperature higher than 353K, the CO_2 adsorption capacity diminishes and reaches 1.18 mmol/g for the APTES-MCF-140 sample. The grafting of APTES on MFCs has caused a partial pore blockage, even though these adsorbents retain a remarkable surface area. This further explains the cause of the reduction in the surface area, yet these adsorbents still can serve as molecular sieves. Based on these findings, it is reasonable to assume that APTES grafted MCFs with a greater surface area could achieve improved CO_2 uptakes due to the increased fraction of physical adsorption sites of these materials.

Furthermore, the effect of temperature and N_2 presence on CO_2 adsorption capacity, CO_2 and N_2 monocomponent isotherms, and binary isotherms with a comparable composition to the post-combustion scenario (15%CO_2/85%N_2) were also examined. Santiago, et al., has stated about these isotherms and the equilibrium models used to fit experimental data at 298, 323, and 348 K for APTES-mesoporous silica [18]. It was observed that the capability of gas adsorption decreases as the temperature rises. Despite evidence of a chemical phenomenon, the data indicate that the physical phenomenon remains dominating. Since this process is exothermic and not an active event, physisorption diminishes as temperature rises. Due to the obvious chemical interactions between the CO_2 and the amino groups, the functionalization procedure has increased the CO_2 uptake capacity and selectivity (concerning N_2). These interactions are especially strong at low pressures and temperatures between 298 and 348 K, as evidenced by adsorption isotherms and microcalorimetry. A summarise of the parameter for the effect of CO_2 adsorption condition on amine-functionalized absorbent is shown in Table 2.

Table 2. Summary table for parameter for section 2.3

Synthesis Parameter	Effect on CO_2 adsorption
The present of pre-adsorb water	APTES-GO has demonstrated a further increase in CO_2 adsorption of 33% at the presence of 10% RH during the synthesis of adsorbent as compared to the corresponding APTES-GO capacity prepared under dry circumstances with the uptake capacity of 1.95 mmol/g and 1.50 mmol/g, respectively [13]. Moreover, the functionalization of APTES with ZIF-8/GO adsorbents (APTES-ZIF-8/GO) in the post-functionalization in water can also increase the CO_2 uptake capacity (0.50mmol/g) when comparing with the absence of pre-adsorb water APTES-ZIF-8/GO (0.21mmol/g) [13].
Different aging temperature	The highest CO_2 adsorption capacity was obtained for the APTES functionalized MCF adsorbent produced at 80°C aging temperature (APTES-MCF-80), which reaches a value of 1.45 mmol/g CO_2 while raw adsorbent of MCF produced at room temperature aging (MCF-RT) only reaches 1.11 mmol/g CO_2. However, the adsorption capacity will increase as aging temperature rises but will show a gradual decrease after certain temperature [17].
Adsorption Parameter	Effect on CO_2 adsorption
Effect of temperature and N_2 presence	Under post-combustion adsorption condition (15%CO_2/85%N_2), the capability of functionalized APTES-mesoporous silica towards CO_2 adsorption decreases as

the temperature rises from 298, 323, and 348 K with the value of 0.58 mmol/g, 0.49 mmol/g and 0.43 mmol/g respectively[18].

2.4 Regeneration of amine-functionalized adsorbent

It is worth mentioning that the ability of an adsorbent to regenerate after several uses is a critical factor for continuous economic use. Adsorbents should have a high density of amino functional groups, the ability to produce vast quantities and be cost-effective to achieve this standard. Sorbents' cycle stability and quick treatment time are highly important in lowering the cost of commercial use in the future. From a study by Dang et al., it was found that APTES-MPS has shown greater stability with no significant reduction in CO_2 capture capacity after 10 adsorption/regeneration cycles [9]. Because of the chemical bonds established between amino groups and MPS, it was perceived that the APTES-MPS is the most stable adsorbent. It was also implied that the APTES-MPS can function at greater adsorption or regeneration temperatures in both humid and dry environments. Meanwhile, Jiang et al. have conducted a study on the stability of APTES functionalized cellulose gel within 20 adsorption-desorption cycles [10]. The CO_2 adsorption capability of the APTES-cellulose gels does not change significantly after 20 adsorption-desorption cycles. Since the amine groups are chemically bonded to the framework of the APTES-cellulose gels, it is indicated that the network and the amine groups are stable under working circumstances.

In another similar study, Li and co-workers have examined the CO_2 adsorption performance of the APTES grafting on alumina-extracted residue (APTES-AR). It was observed that this adsorbent could effectively be regenerated at 383K and maintain a steady uptake in five repeated adsorption-desorption cycles [11]. These findings showed that APTES-AR might be a good sorbent for CO_2 adsorption. Furthermore, the grafting procedure was carried out in this study by covalent bonding between the surface silanol group of supports and amino silane molecules. As a result, the grafted sorbents have good thermal stability and CO_2 selectivity. The CO_2 adsorption capacity slightly drops after five cycles from 1.05 mmol/g to 0.98 mmol/g, while a high regeneration temperature of 383K has reduced the capacity loss by only around 5.7%. This shows that the functional sorbent of the amine has a desired cycle stability.

Muchan et al., also studied the regenerability of the APTES functionalized adsorbent. MCM-41 with micropore channels took around 8 minutes to release CO_2, requiring more energy for regeneration [12]. Meanwhile, the CO_2 was released by SBA-15 and KIT-6 in around 3 minutes. With a cubical linked high pore diameter, KIT-6 has provided excellent N_2 flow transmission for purging the CO_2, resulting in the lowest regeneration energy. In the meantime, APTES-modified adsorbents with the greater primary amine loading in SBA-15 have successfully generated more stable carbamate during the adsorption process, resulting in higher energy demand for regeneration. Even the APTES MCM-41 has a lower amine loading than that of APTES SBA-15, more energy is required for regenerability. This was due to the existence of smaller size channels for the flowing gas, hence requires a longer time to remove the CO_2 from the adsorbent, resulting in the greatest energy demand. The benefits of KIT-6's greater pore size and interconnected porous structure resulted in a high CO_2-desorption performance and the lowest energy consumption for APTES KIT-6 regeneration. Also, after five adsorption/desorption cycles, the stability of the amine-modified adsorbent was linked to the stability of the amine sites. In this case, the adsorbent's porous structure is unimportant. The reduction in CO_2 adsorption capacity may be due to the tight link between CO_2 and the primary amine in APTES, which results in inadequate desorption of pre-adsorbed CO_2 at 373K.

3. Future Prospect and Recommendation

For an eco-friendly atmosphere, carbon capture technologies need to be established to have the ability to reuse the released industrial gases by converting them into reusable power or fuel sources. Hence, we should discover the unique and new composites to further enhance the CO_2 uptake ability of APTES functionalized adsorbents. Among the proposed adsorbents, APTES based chemical adsorbents with large surface area support and high optimum amine loading need to be further extensively investigated

due to their significant outcomes such as high CO_2 adsorption capacity, fast adsorption-desorption rates, high tolerance toward moisture, and high CO_2 selectivity. Hence, further study on APTES functionalized-solid adsorbent is encouraged in fabricating a functionalized adsorbent with excellent adsorption performance that is applicable for practical technologies.

4. Conclusion

In conclusion, several carbon capture technologies have been studied and developed to minimize the cost of CO_2 capture by learning from experience while meeting a sufficient reduction of CO_2 emissions. Meanwhile, this review focus on the usage of adsorption technology to capture CO_2. A general review for CO_2 capture using APTES functionalized adsorbent was systematically presented in this work. APTES can improve the CO_2 capture ability for different adsorbents according to different conditions such as the amount of amine loading, the condition for CO_2 capture, and even the condition used for amine functionalization. Besides, APTES functionalized adsorbents are also able to possess better stability and regeneration compared to pristine adsorbents due to the formation of the chemical bond between APTES and the adsorbents.

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