Review Article

Adsorbents for Noxious Gas Sequestration: State of the Art.

ABSTRACT

Adsorbents such as metal organic frameworks (MOFs), polymers, activated carbon (AC) and membranes are becoming prominent for CO_2, SO_2, H_2S and NH_3 capture and in some cases, storage. Using the standard adsorbent properties (SAPs) such as adsorption capacity, selectivity, permeability/permeance, regenerability and reusability, ease of functionability and tunability, thermal and chemical stability etc., suitable candidates for noxious gas sequestration can be determined. In order to foster the development and selection of a more efficient adsorbent, a proper documentation of adsorbent performance in terms of SAPs, is crucial. In this study, a critical review of metal organic framework (MOF), polymer, activated carbon (AC) and membrane adsorbents was performed. Using the SAPs, an up to date comparative analysis was done to select the best performing adsorbents. The results of the comparative analysis were then used to categorize the adsorbents suitability for pre – combustion and post - combustion applications. A perspective of future study on adsorbents for noxious gases sequestration, was also presented.

Keywords: sequestration; adsorbent; metal organic framework; polymer; activated carbon; membrane; noxious gases.

1. INTRODUCTION

The world's energy demand is continuously increasing with its population growth. A significant part of this energy would be provided by fossil fuels (coal, crude oil and natural). 73.25% of world energy consumption would be provided by fossil fuels by 2040 [1]. Figs. 1 to 3 show global natural gas, crude oil and coal reserves respectively from the years 2016 to 2018, and a projection for production and consumption into the future [2–5]. It is evident from the charts that production and consumption of these fossil fuels would continuously increase into the future (except for coal with a slight reduction). These trends would cumulatively result in the increase in noxious gases released into the atmosphere. These harmful gases such as CO_x, [6], CH_4 [7], NH_3, SO_x, NO_x, H_2S [8], Volatile Organic Compounds (VOCs) and volatile organic gases [9] pose a high environmental risk [10]. This therefore necessitates the management of air quality in order to ensure a sustainable environment.

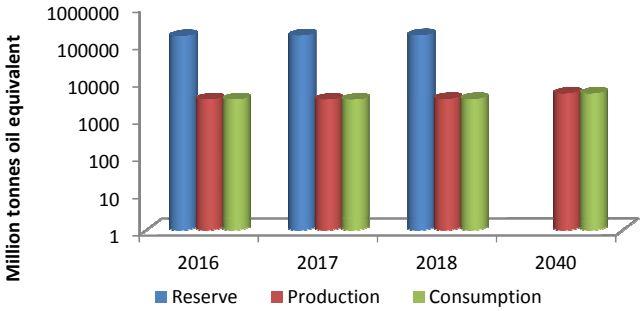

Fig. 1. Natural gas outlook (Source: [2–5])

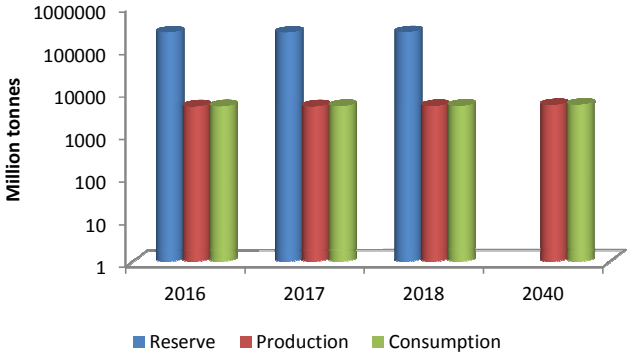

Fig. 2. Crude oil outlook (Source: [2–5])

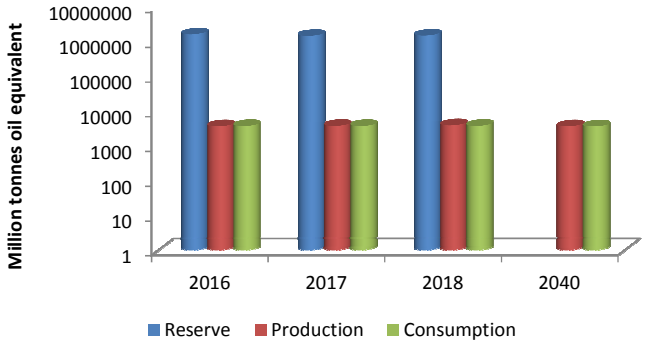

Fig. 3. Coal outlook (Source: [2–5])

Different materials and methods [11–18] have been reported for the separation and capture of hazardous gases either from process systems or the environment. Amongst these compounds, adsorbents such as metal organic frameworks (MOFs), polymers, activated carbon (AC) and membranes, have been considered as promising candidates for gas separation and storage, due to their large surface area and pore volume, good thermal and chemical stability, ease of functionability and tunability, low regeneration cost and high selectivity. These adsorbents can be easily modified for specific applications through pre- and post-functionalization of the structure [19–21]. Adsorbent utilization becomes more feasible when its CO_2 adsorption capacity is above 3 mmol/g [22].

For the purpose of this study, an up to date review of the performance of MOFs, polymers, AC and membrane adsorbents are considered. The major focus of this study therefore, was to identify the best performing adsorbents for noxious gas sequestration and then proffer suitable areas for their application.

2. ADSORBENTS FOR CAPTURE OF HARMFUL GASES

Among the numerous types of adsorbents for the capture of harmful gases, MOFs, polymers, membranes and AC are in the forefront of research for harmful gas sequestration as a result of their promising structural properties. *Adsorption, permeability, selectivity, flux rate, reusability and regeneration* are key parameters that determine the deployment of MOFs [21], membranes [23] polymers [24] and AC [25,26] for sequestration of harmful gases in various process systems and conditions. These conditions are imperative for the industrial deployment of these adsorbents for gas capture and storage.

2.1 Metal Organic Frameworks (MOFs)

Metal Organic Frameworks (MOFs) are an emerging class of porous materials constructed from metal-containing nodes and organic linkers [27]. Due to the strong bonds that exist between the metal-containing nodes [also known as secondary building units (SBUs)] and organic linkers, MOFs usually boast of a structure with permanent porosity and open crystalline frameworks as shown in Fig. 4. The organic spacers or the metallic SBUs can be altered to control the pore environment of the MOF [28]. Their inherent characteristics/advantages such as large surface area, ease of functionalization, kinetic diameter, electric properties, Open Metal Sites (OMS), high porosity and tuneable size of pores [29] have made them very attractive compounds in applications such as gas storage and separation, catalysis and sensing [30,31]. The ease with which SBUs and organic linkers are changed and altered has led to the synthesis of thousands of various MOF structures. As a result, the structures and properties of MOFs can be designed and systematically tuned by the choice of building blocks used for the synthesis of the framework [32]. Various strategies have also been reported for improving the performance of MOFs [33].

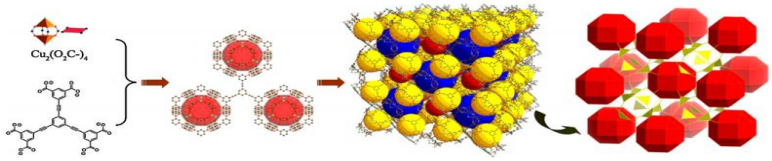

Fig. 4. Crystalline structure of Metal Organic Frameworks [32]

MOFs have been investigated for optimization of structure functionality. In this regard, MOFs have been reported to exhibit promising potential for sequestration of gases such as CO_2, H_2S, CH_4, NH_3, NO_x, SO_x etc. [8,14,34–39]. The works of [13,14,40–66] highlight MOFs for CO_2, SO_2, H_2S and NH_3 sequestration at pre- and post-combustion conditions.

2.2. Polymers

Porous Organic Polymers (POP) are composed of organic building blocks connected through covalent bonds, exhibiting thermal and chemical stabilities, large surface area, ease of synthesis and low density [67]. There are two classes of POP. They include; The amorphous (conjugated microporous polymers (CMP) [68], covalent triazine framework [18], porous aromatic framework [18], hyper-cross linked polymers (HCP) [69]) and polymers of intrinsic [70] and crystalline types (covalent organic polymers) [71].

Different polymers have been synthesized for harmful gases sequestration at different process conditions [72] and modification through pre-synthetic and post synthetic functionalization [73] have been reported for improved performance for specific applications . [15]. The agents used for functionalization are compounds that increase the affinity of porous polymers for a specific noxious gas. For instance, for CO_2 adsorption, amino functional groups [74], –N heterocycles [75], phenolic motifs [15] are utilized. The method of synthesis plays a key role in the structure of a polymer which invariably affects the adsorption capacity. The different monomers (building blocks) and methods of synthesis are explained by [76]. Polymers have also shown excellent reusability [75] and low heat of adsorption [77]. The works of [11,15,18,69,73,78–85] highlight the use of polymers for CO_2, SO_2, NH_3 and H_2S sequestration.

2.3. Activated Carbon (AC)

AC has been investigated for capture of noxious gases [86,87]. This is due to reduced cost of production, large surface area, ease of modification of pores, good thermal and chemical stability, hydrophobic nature, stability in the presence of heat and chemical resistance [88]. AC shows promising potential for practical applications in terms of balance of performance [89] considering cost of production, benign effect on the environment, availability of precursor materials [90,91] and sustainability [92], and have been reported to exhibit reusability, promising adsorption kinetics [26] and stability after several sorption cycles [63], requiring low regeneration energy [93]. A key determinant to the adsorption performance of AC is the type of precursor used in its synthesis. Different precursors have been reported in the literature for the production of AC.

They include bamboo [94], petroleum coke [95], rice husk char [26] wood [96], coconut shell [97], sugarcane bagasse [91], argan fruit shells [98], pinewood shavings char, biochar [89] etc. Amongst these precursors, biochar stands out as it exhibits high porosity and high amount of fixed carbon that can be processed to AC with high micro porosity [89]. Therefore, biochar precursors should receive further investigation in its use for the production of AC for gas sequestration. It is imperative to state that these precursors should have low ash and volatile matter content so as to produce AC with micropores on the surface of the structure for adsorption abilities.

AC have been investigated for SO_x and NO_x [99,100], H_2S [101] and CO_2 [100] sequestration at different process conditions. In order to optimize capture and selectivity of AC for specific gases, modification of the structure to increase its affinity for specific gases have been reported [102–108]. Various studies on the use of AC for CO_2, SO_2, NH_3 and NO_x sequestration, have also been reported [90,91,93,98,108,109].

2.4. Membranes

Membranes basically function as filters as shown in Fig. 5. They are used for separation [110]. Different researchers have reported membrane use for capture of harmful gases in literature [17,111,112] as they are environmental benign and efficient in energy consumption [113] and exhibit technical and cost-related merits [114]. Key parameters that determine feasibility of membranes for industrial applications are *permeability and selectivity* [115]. Membranes should therefore possess high permeability, permeance, high selectivity, low cost of production and regeneration, good chemical and thermal stability, and ability to resist plasticization [116,117], in order for it to be feasible. Progress in this regard have been recorded in literature where properties of membranes have been optimized even though challenges such as high cost, low physical and chemical stability, low selectivity and low hydrothermal stability still persist [118] . This structure optimization has resulted in the synthesis of different class of membranes [110,119–122].

Various studies on the use of membrane for the capture of CO_2 and H_2S, have also been reported [110,112,122–126].

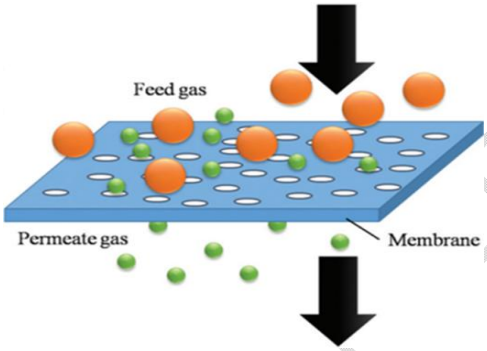

Fig. 5. Separation of different molecules using membrane [118]

3. PERFORMANCE EVALUATION OF ADSORBENTS USING SELECTED SAPS

This section considers the performance of adsorbents reviewed in this study for industrial applications. Although adsorbents for carbon sequestration have not attained the stage of commercial applications [127], they are currently in their demonstration phase. Parameters such as *adsorption capacity, selectivity, permeability/permeance (for membranes), regeneration/reusability, thermal and chemical stability,* were used to rank these adsorbents for the purpose of determining the most efficient adsorbent and suitable points for their application. Adsorption capacity was used as the highest-ranking property. Only the best performing adsorbent is reported for each SAP category. The industrial applications considered in this study include pre-combustion and post -combustion conditions.

3.1. CO_2 Adsorption capacity at pre-combustion conditions

Pre-combustion conditions typically occur at relatively high pressures and / or low temperatures. Such conditions can include process systems such as natural gas, biogas sweetening, etc. Polymers and AC have shown high adsorption capacities at high pressures amongst adsorbents reviewed in this study. Polymers PPN-4 [128] and PAF-1 [129]

Comment [D1]: and/or

exhibited the highest adsorption capacities of 48.20 mmol/g and 29.55 mmol/g at pressures of 50 bar and 40 bar respectively at ambient temperatures. ACs LSB3-800 [86] and SBL-PNP-1-4-750 [130] also showed high adsorption capacities of 20.9 mmol/g and 19.65 mmol/g at pressures of 20 bar each at 298K. AC SBL-PNP-1-4-750 [130] was the only adsorbent that showed high adsorption capacity of 16.2 mmol/g at a high temperature of 1023K, at 20 bar.

Membranes showed suitability for pre-combustion separation of CO_2. They have been shown to function within pressure range of pre-combustion carbon capture. Membranes COF 300/6FDA-DAM MMM and COF 300/Pebax MMM [131] can be applied in pre-combustion conditions if their thermal stability at high temperatures is improved.

MOFs did not show high adsorption capacities as much as polymers and AC for pre-combustion application. The highest performing MOFs for pre-combustion conditions were HKUST-1 and MIL-101 (Cr) [130] with adsorption capacities of 8.07 mmol/g and 7.19 mmol/g at pressures of 10 bar and temperatures of 303K.

3.2. CO_2 Adsorption capacity at post-combustion conditions.

Post combustion applications occur basically at approximately atmospheric pressure of 1 bar and high or low temperatures [132]. At practical post combustion conditions of flue gases from systems such automobiles, petrol generators, motorcycles, gas turbine power plants, oil turbine plants, coal fired plants, water pyrolysis and cement production, only a few adsorbents were found to be applicable. Most of the adsorbents showed a decrease in working capacity as temperature increased and ultimately resulted in the decomposition of the structure which implied that the adsorbents cannot be used at relatively high temperature conditions. This can be attributed to the fact that as temperature increases, adsorption capacity of adsorbents such as AC decreases [133]. The low adsorption capacities of AC with values between 0.2 mmol/g to 1.80 mmol/g at 1 bar and 373K [104] and that of NORF700 [134] and NCLK3 [135] with adsorption capacities of 2.10 mmol/g and 2.00 mmol/g at 1 bar and 323K, support this claim. Polymers, AC and MOFs do not exhibit high adsorption capacities for CO_2 in post-combustion conditions at high temperatures. MOFs 1-een and 1-dmen [136], TAEA modified MIL-101 (Cr) [45] and 1-nmen [136] had the highest adsorption capacities of 5.05 mmol/g, 4.34 mmol/g, 4.05 mmol/g and 2.92 mmol/g respectively, at ~1 bar and 313K. Amongst these MOFs, 1-dmen [52] has shown promising potential for practical applications due to its high selectivity of 554 for CO_2 in a binary mixture of CO_2/N_2. It is therefore evident that these values for adsorption capacity are not as high as those recorded in pre-combustion conditions as pressure increase results in increase in adsorption capacities [137].

Most adsorbents showed good adsorption capacities for post combustion CO_2 capture at ambient temperatures, with polymer and AC exhibiting the highest adsorption capacities. Polymer IHBPA (TEPA) [138] and PI-COF-2 [80] had adsorption capacities of 7.65 mmol/g and 5.8 mmol/g respectively at 1 bar and 298K while AC CuO NP-AC [108], ARG-K-Im [98] and DAC-AC-CO_2 [98] had adsorption capacities of 6.72 mmol/g, 5.63 mmol/g and 5.52 mmol/g respectively at 1 bar and 298K. MOF UTSA-120a [46] was the highest performing MOF in this regard with adsorption capacity of 5.00 mmol/g at 1 bar and 296K, all other MOFs performed below this value in this study. Considering the working temperatures and pressures of the adsorbents, they are mostly suited for pre- and post - combustion capture at *ambient temperatures*.

Comment [D2]: explain the possible reason for low adsorption capacity of the remaining adsorbent at high temperature

Comment [D3]: whenever you discuss a literature, you should make your contribution as to the possible cause of the obtained result

3.3. CO_2 Selectivity of adsorbents at pre- and post-combustion conditions.

In terms of selectivity for CO_2 in flue gas stream, MOFs have shown exceptional selectivity that outperformed other adsorbents such as polymers, adsorbents and membranes. This can be attributed to their ease of functionalization using CO_2-philic functional groups. MIL-140 [41] and UTSA-120a [46] showed one of the highest selectivity of 1900 and ~600 for CO_2 in binary mixtures (CO_2/N_2). An extremely high selectivity of 7531 for CO_2/N_2 binary mixture was recorded for MOF MFUM-1(Cu) [139] without information on its adsorption capacity. MOFs 1-dmen [136] and 1-ipen [136] have also been reported to exhibit selectivities of 554 and 273 respectively.

3.4. Regenerability and reusability of adsorbents at pre- and post-combustion conditions.

Some of the adsorbents can be regenerated and re-used for CO_2 capture without losing their adsorption capacities. MOF 1-een [136] has been reported to retain its adsorption capacity after 600 sorption cycles, the highest recorded in this study. Other adsorbents such as AC NSCS-4-700 [63], CNS-AC [90], DAC-AC-CO_2 [109], polymer (IHBPA (TEPA) [138] and MOFs 1-dmen [52] and 1-een [136] have been shown to retain their adsorption capacities between five to eleven sorption cycles.

3.5. Thermal stability of adsorbents at pre- and post-combustion conditions.

Polymer CQN-1g [52] had the highest thermal stability at 773K. Other polymer compounds such as TAP-3 [15] and NHC-CAP-1 [75] had thermal stabilities up to 573K and 373K respectively while AC NSCS-4-700 [75] had thermal stabilities up to temperatures of 473K. Some MOFs such as MFM-305 [13], MIL-140 [41] and Cu-Sp5 [140] have been shown to be thermally stable at temperatures of 723K, 573K and 503K respectively. Some adsorbents in this study therefore exhibit thermal stabilities at high temperatures obtainable in most industrial processes. This shows that the adsorbents have potential for use at high temperature conditions. However, literature in this regard remains scarce.

3.6. Permeance and selectivity for CO_2 of membranes at pre- and post-combustion conditions.

Membranes have also shown promising permeance and selectivity for CO_2 in flue gas mixtures. UiO-66CN@sPIM-1 [120] recorded the highest CO_2 permeance amongst reviewed membranes with a value of 12063 Barrer and selectivity (CO_2/N_2) of 53.5 at atmospheric conditions. MoS_2-SILM membrane [141] has been shown to exhibit the highest selectivity of 462 for CO_2. Also, membranes such as MOF-801/PEBA MMM [141] and COF-5/Pebax [126] with selectivities of 66 and 49.3, respectively for SCO_2/N_2 . Most of the membranes recently synthesized exhibit high CO_2 permeance and promising selectivity for CO_2 separation which exceeded the standard values for industrial use of 2250 for CO_2 permeability and >30 for selectivity. The fact that most membranes have good permeance and selectivity for CO_2, makes them well suited for industrial gas separation process applications.

Table 1. Selected CO_2 adsorbents with the highest adsorption capacity.

Material	Adsorbent	CO_2 Uptake (mmol/g)	P (bar)	T (K)	Slcty (CO_2/N_2)	Stability	Cycles of Performance	Potential point of application
PPN-4	Polymer	48.20	50	298	-	-	-	Pre-combustion capture of CO_2
PAF-1	Polymer	29.55	40	298	-	-	-	Pre-combustion capture of CO_2
LSB3-800	AC	20.9	30	298	-	-	-	Pre-combustion capture of CO_2
SBL-PNP-1-4-750	AC	19.65	20	298	-	-	-	Pre-combustion capture of CO_2
SBL-PNP-1-4-750	AC	16.2	20	1023	-	-	-	Pre-combustion capture of CO_2
HCP-1	Polymer	13.1	30	298	-	-	-	Pre-combustion capture of CO_2
NSCS-4-700	AC	11.68	8	298	-	-	Showed no loss of adsorption capacity after 10 sorption cycles at 473K regeneration temperature	Pre-combustion capture of CO_2
CNS-AC	AC	8.36	30	303	-	-	Adsorption performance remained unchanged after the 6^{th} sorption cycle	Pre-combustion capture of CO_2
HKUST-1	MOF	8.07	10	303	-	-	-	Pre-combustion capture of CO_2

Comment [D4]: introduce Table 1 and 2 in the preceeding section

IHBPA (TEPA)	Polymer	7.65	1	298	-	Thermal stable up to 363K	Maintained adsorption capacity after 10^{th} sorption cycle.	Post combustion capture of CO_2 at ambient temperatures
MIL-101 (Cr)	MOF	7.19	10	303	-	-	-	Pre-combustion capture of CO_2
CuO NP-AC	AC	6.72	1	298	-	-	-	Post combustion capture of CO_2 at ambient temperature
PI-COF-2	Polymer	5.8	1	298	-	-	-	Post combustion capture of CO_2 at ambient temperature
ARG-K-Im	AC	5.63	1	298	-	-	-	Post combustion capture of CO_2 at ambient temperature
DAC-AC-CO_2	AC	5.52	1	298	28.4	-	Showed stability and maintained its initial adsorption capacity up to 11^{th} sorption cycle	Post combustion capture of CO_2 at ambient temperature; selectivity has to be improved upon for viable applicability
1-een	MOF	5.05 4.04	1 0.15	313	293	-	Working capacity dropped from 13.89wt% to 12.36wt% at the 100^{th} sorption cycle	Sequestration of CO_2 flue gases at post combustion conditions from automobiles, motorcycles, generators etc.

UTSA-120a	MOF	5.00	1	296	~600	-	-	Post combustion capture of CO_2 at ambient conditions due to high selectivity
CQN-1g	Polymer	4.57	1	298	-	Thermally stable up to 773K	-	Post combustion capture of CO_2 at ambient temperatures; Possibility of practical use for CO_2 capture.
1-dmen	MOF	4.34	1	313	554	-	Retained its adsorption capacity after 7^{th} sorption cycle	Post combustion capture of CO_2 from exhaust gas of automobiles, petrol generators, motorcycles etc.
NSCS-4-700	AC	4.27	1	298	-	-	Retained adsorption capacity after 10 sorption cycles at 473K regeneration temperature	Post combustion capture of CO_2 at ambient temperature
TAEA modified MIL-101 (Cr)	MOF	4.06	0.15	313	-	-	-	Post combustion capture of CO_2 from exhaust gas of automobiles, petrol generators etc.
1-ipen	MOF	4.05	1	313	273	-	-	Post combustion capture of CO_2 at ambient temperature

Table 2: CO_2 permeance and selectivity capacity of membranes

Material	P (bar)	T (K)	CO_2 permeance (Barrer[a]/GPU[b])	CO_2/N_2	CO_2/CH_4	Potential point of application
UiO-66-CN@sPIM-1	1.4	298	[a]12063	53.5	-	Separation of CO_2 from binary air mixture (CO_2/N_2) at atmospheric Conditions.
COF 300/6FDA-DAM MMM	8	298	[a]8257	-	75	Pre-combustion separation of CO_2
COF 300/Pebax MMM	8	298	[a]8054	-	110	Pre-combustion separation of CO_2
TFC#1	3	298	[b]8010	35.8	-	-
TFC#6	3	298	[b]3010	55.7	-	-
FIHM-PEGDME-500-180	3.5	303	[a]1566.8	35.1	-	-
MoS_2-SILM	1	293	[b]200	462	-	Post combustion capture of CO_2 at ambient temperatures

1 Barrer = 10^{-10}cc (STP)cm cm^{-2} s^{-1} $cmHg^{-2}$
1 GPU = 10^{-6}cc (STP)cm^{-2} s^{-1} $cmHg^{-1}$

3.7. Adsorbent performance for other noxious gases sequestration at pre- and post-combustion conditions.

For NH_3 capture at post combustion conditions at ambient temperatures, polymer PCP-1 [142] had the highest adsorption capacity of 22.8 mmol/g as shown in Table 3. MOF Cu_2Cl_2BBTA [143] and MOF-4 [143] also had good adsorption capacities of 19.79 mmol/g and 17.8 mmol/g respectively. Unfortunately, the thermal and chemical stability of these adsorbents for NH_3 capture were not investigated by the authors. Same applies to their regenerability and reusability except for Polymer PCP-1 [142] which showed very low reusability potential.

Comment [D5]: what could be the possible reason for the low reusabilty, could it be due to reaction between adsorbant and the active side, leaching etc.?

MOFs, polymers, AC and membrane have been reported to also sequester noxious gases such as SO_2, NH_3 and H_2S, considerably at pre-combustion and post combustion conditions, despite the chemical stability challenge posed by compounds such as SO_2 and H_2S to adsorbents. For SO_2 capture, MOF compounds such as MOF-3 [56], NH_2-MIL-125 (Ti) [144],

MFM-300 (Sc) [55] and MIL-160 [144], MOC-1 and MOC-3 [54] had better adsorption capacity at post combustion conditions at ambient temperatures, as shown in Table 4. Unfortunately, none of these compounds were investigated at temperatures consistent with Flue Gas Desulfurization (FGD) systems.

MOF MIL-53 (Al) TDC [57] was found to be the highest performing adsorbent for H_2S capture at post combustion conditions at ambient temperatures, more than Polymers PM_{012}@Ui-66@H_2S-MIPsM [145] and BPP-5 [146] as shown in Table 5. Furthermore, Polymer BPP-5 [146] had a better chemical stability and potential for regenerability and reusability. MOF MIL-101@M-0.5-0.5 [147] was found to be the only adsorbent with high potential for H_2S capture at pre-combustion conditions with adsorption capacity of 36.1 mmol/g at 10 bar and 298K. Membrane NbOFFIVE-1-NI/6FDA-DAMMMM [146] showed capacity to simultaneously separate CO_2 and H_2S from methane (CH_4), with a selectivity of 48 for CO_2+H_2S over CH_4 and a permeance of 950 CO_2+H_2S. This compound has potential for natural gas sweetening if the permeance property is improved.

Table 3. Selected NH_3 adsorbents with the highest adsorption capacity

Material	Adsorbent	NH_3 Uptake mmol/g	P (bar)	T (K)	Cycles of Performance	Potential Point of Applications
PCP-1	Polymer	22.3	1	298	Adsorption capacity reduced at 3rd sorption cycle; Reduction of 5.2 mmol/g between 1st and 2nd sorption cycles was recorded.	NH_3 capture at ambient conditions
Cu_2Cl_2BBTA	MOF	19.79	1	298	-	NH_3 capture at ambient conditions.
MOF-4	MOF	17.8	1	298	-	NH_3 capture at ambient conditions.

43 **Table 4: Selected SO_2 adsorbents with the highest adsorption capacity**
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Material	Adsorbent	SO_2 Uptake (mmol/g)	P (bar)	T (K)	Selectivity	Stability	Cycles of Performance	Potential point of application
MOF-177	MOF	25.7	1	293	-	Chemically unstable	-	Not suitable for practical applications.
MOF-3	MOF	10.9	1	298	-	-	-	SO_2 capture at ambient conditions.
NH_2-MIL-125(Ti)	MOF	10.8	0.95	293	SO_2/CO_2 – 47-55	-	Showed irreversible adsorption capacity; working capacity reduced at 2nd cycle of performance.	SO_2 capture at ambient conditions.
MFM-300(Sc)	MOF	9.4	1	298		-	Adsorption capacity remained unchanged after 10 sorption cycles; regeneration occurred at room temperature.	SO_2 capture at ambient conditions
MIL-160	MOF	7.2	0.95	293	SO_2/CO_2 – 124-128	Thermal and chemical stable	Exhibited good adsorption stability with slight reduction in sorption capacity after 5 sorption cycle	SO_2 capture at ambient conditions

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Table 5. Selected H_2S adsorbents with the highest adsorption capacity

Material	Adsorbent	H_2S Uptake (mmol/g)	P (bar)	T (K)	Stability	Cycles of Performance	Potential point of application
MIL-101@M-0.5-0.5	MOF	36.1 7.63	10 35	298	-	-	Pre-combustion capture of H_2S from syngas stream.
MIL-53 (Al)-TDC	MOF	18.1	1	303	Chemically stable in the presence of H_2S	Adsorption capacity was retained after 5 sorption cycles; structure exhibits low temperature of 473K for regeneration; regeneration can be achieved at temp. of 338K.	Integrated Gasification Combined Cycle (IGCC) for H_2S capture at ambient temperatures
BPP-5	Polymer	17.7	1	298	Superior stability in extremely basic conditions	Author suggested that structure will keep working capacity after various adsorption-desorption cycles	H_2S capture at ambient conditions

4. CONCLUSIONS AND PERSPECTIVES

In this review, the performance of selected categories of adsorbents for noxious gas sequestration have been evaluated. The suitability of the adsorbents with the highest SAPs such as adsorption capacity, selectivity, permeance, regenerability and reusability, thermal and chemical stability was determined for pre-combustion and post combustion industrial applications. Perspectives of future studies was also presented.

In terms of adsorption capacity, Polymers, AC and MOFs are suitable for CO_2 adsorption at pre- and post – combustion conditions. Some polymers and ACs were found to have very high adsorption capacities compared to MOFs. MOFs on the other hand, having the highest adsorption capacities are best suited for SO_2 capture. For H_2S and NH_3 adsorption, MOFs and Polymers had the highest adsorption capacity, making them more suitable than ACs.

MOFs have been revealed to show exceptional selectivity for CO_2 and SO_2 in binary mixtures of CO_2/N_2 and SO_2/CO_2 respectively, making it a suitable candidate for CO_2 and SO_2 capture. Most membranes showed selectivity and permeance capacities suitable for industrial applications (>30 for selectivity and >2250 for permeance).

Most of the temperature conditions at which these adsorbents were investigated are below practical temperature conditions obtainable in post – combustion process systems. This therefore creates a challenge in their industrial deployment. It is therefore needful to investigate the capture and storage capacities of these absorbent at higher temperatures, so as to ensure their industrial applicability for improved environmental sustainability. Also, information on the selectivity, stability, regenerability and reusability of most of the adsorbents, were not reported. It becomes imperative for these parameters to be properly investigated and reported. The adsorption capacities of MOFs for CO_2, Polymers and ACs for SO_2, as well as ACs for H_2S and NH_3, should be further investigated and improved upon.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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