

## **Efficacies of Carbon Based Adsorbents for Carbon Dioxide Capture**

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## Abstract

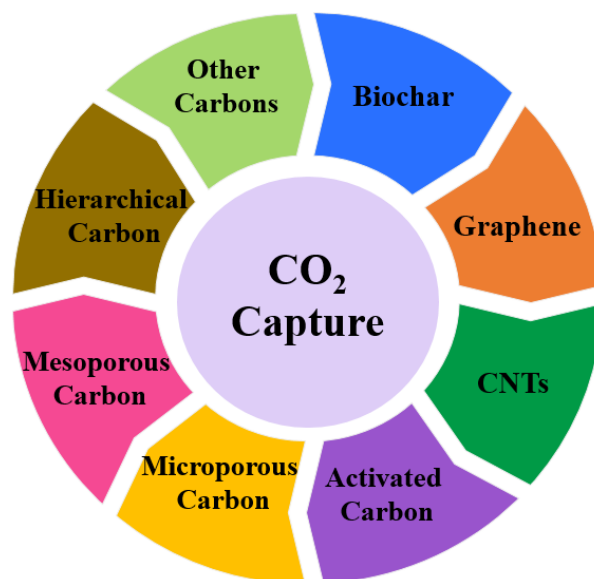
Carbon dioxide (CO<sub>2</sub>), a major greenhouse gas, capture and separation has recently become a crucial technological solution to reduce atmospheric emissions from fossil fuel burning. Thereafter, many efforts have been put forward to reduce the burden on climate change by capturing and separating them especially from larger power plants by the utilization of different technologies. Those technologies have often suffered from high operating cost and huge energy consumption. On right side, physical process such as adsorption is very cost effective process which have been widely used to adsorb different contaminants including CO<sub>2</sub>. Henceforth, this review covers the overall efficacies of CO<sub>2</sub> capture by the utilization of carbon based materials through adsorption technology. Subsequently, we also address the associated challenges and future opportunities of carbon based materials (CBMs). For CO<sub>2</sub> capture, it was found that CBMs followed the order of carbon nanomaterials (i.e., graphene, graphene oxides, carbon nanotubes and their composites) < mesoporous -microporous or hierarchical porous carbons < biochar and activated biochar < activated carbons.

**Keywords:** CO<sub>2</sub> capture, Activated carbon, Carbon nanomaterials, Adsorption, Surface area.

## 1. Introduction

Due to the burning of fossil fuels, the concentration of CO<sub>2</sub> has been increasing significantly. Therefore, increase concentration of CO<sub>2</sub> in the atmosphere causes global warming leading to significant environmental disasters [1-3]. The atmospheric concentration of CO<sub>2</sub> has been increasing enormously in the recent days. For example, CO<sub>2</sub> concentration hits up to 415.26 ppm at the Mauna Loa Observatory in Hawaii [1]. It is predicted that, in 2050, atmospheric CO<sub>2</sub> concentration will reach up to 550 ppm [1]. However, the majority of the emissions are occurred through human activities. This will have become very harmful for humans. Hence, there is a great urgency to reduce the CO<sub>2</sub> level from atmosphere through utilization of different technologies. The intergovernmental panel on climate change recommended three fundamental steps for carbon capture and storage for combating carbon dioxide emissions. They involve: (i) separation through capture, (ii) transportation, and (iii) storage of CO<sub>2</sub> [4]. Although enough progress has been made on transportation and storage of CO<sub>2</sub>, but still progresses are going on the capture of CO<sub>2</sub> through different processes [5]. Membrane separation techniques have been utilized for the capture of CO<sub>2</sub> at low pressure. However, these kind of technology often suffers from high operating cost, and they are non-energy efficient to compress the feed gas [6]. On the other hand, porous based materials to adsorb CO<sub>2</sub> are a very promising methods which can be utilized at different operating conditions. Hence, compared to the liquid adsorption based technology (such as amine

based adsorption technology), CO<sub>2</sub> capture via solid state materials (e.g., adsorption technology) is very cost effective, easy to design, functional surface, hydrophobicity, need low energy consumption, simple operation and easy regeneration of adsorbents [7-11]. Solid adsorbents are alkaline metal oxides and hydroxides, zeolite, metal organic frameworks, porous polymers and carbon based materials (CBMs) including activated carbon, biochar, nanocarbons (CNTs and graphene), mesoporous and microporous carbons and so on. Among them CBMs have great potential in the capture of CO<sub>2</sub> due to their high surface area, well defined porosities, larger pore volume, chemical stability, and easy handling [1,7,12-14].



**Scheme 1:** CBMs for CO<sub>2</sub> capture through adsorption technology.

**Scheme 1** demonstrates a brief summary of CBMs which are used for the adsorption of CO<sub>2</sub>. Although there are many reviews on CO<sub>2</sub> capture, however, to our best knowledge none of them was discussed on the overall efficacy of CMBs to capture

CO<sub>2</sub>. Therefore, the main objectives of this review is to demonstrate the comparative analysis on the efficacies of different CBMs. The subsequent objectives to give an overall performance of CBMs together with the major associated challenges and future opportunities on the potential applications of CBMs for CO<sub>2</sub> capture. Hence, we believe that this review will be very helpful for the different researchers and stockholders for the understanding on the recent trends on CMBs performances for CO<sub>2</sub> capture through adsorption technology.

## **2. Efficacy of CBMs for CO<sub>2</sub> Capture**

CBMs are considered as the most performance materials for CO<sub>2</sub> capture [11]. CBMs have specific properties as mentioned above, which are highly needed for efficient CO<sub>2</sub> capture. There are many types of carbon based adsorbents for CO<sub>2</sub> capture, but they can be broadly classified as biochar, nanocarbons materials (e.g., graphene, CNTs, nanocarbons), activated carbons (ACs), different microporous, mesoporous and hierarchical carbons with or without doping with other inorganic, organics, metal components or metal atoms. All of these CBMs have significant surface area, pore density, volume, pore size, high stability and sustainability properties which are basically prime requirements of CO<sub>2</sub> capture. Therefore, this review will basically cover the performance of biochar, different nanomaterials such as graphene, graphene oxides and carbon nanotubes (CNTs), ACs, microporous, mesoporous and hierarchical porous

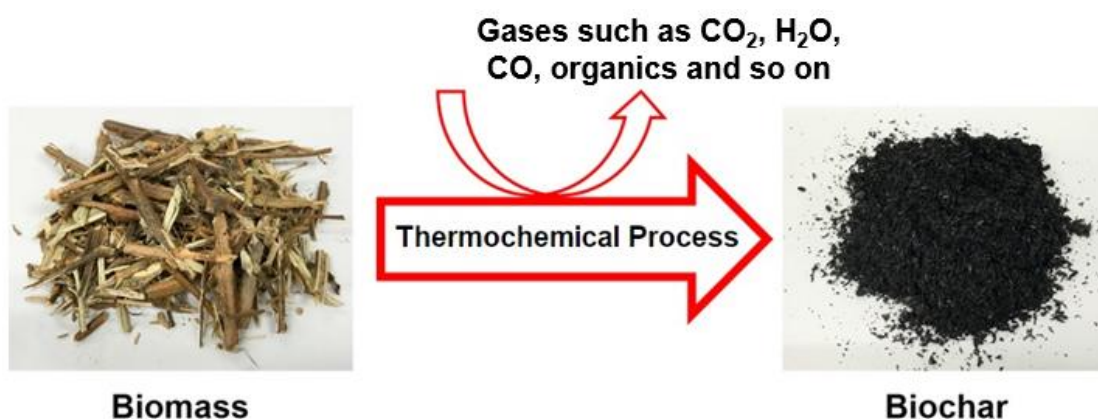
carbon materials together with their composite materials. Following subsections will basically address on CO<sub>2</sub> capture efficacies using those CBMs.

### ***2.1. Biochar for CO<sub>2</sub> Capture***

Recently, among various adsorptive materials (e.g., AC, graphene, carbon fibers etc.), biochar has gained considerable attention as an ecofriendly and cost effective materials for CO<sub>2</sub> sequestration, as catalysts, as greenhouse gas capturing material, as water treatment and soil remediation materials [15-17]. Biochar is a carbon-rich material prepared from natural resources having high surface area, hydrophobic nature, and easy regeneration [18]. This makes the biochar an attractive material for researchers to control the emission of different gaseous pollutants in the environment [19,20]. Biochar can be synthesized from cheap and easily available biomass feedstock's and wastes from different industries (e.g., dairy manure, forestry, agricultural) and many other bio-wastes [21-23]. Basically, biomass resources are composed of C, O, H structures and some of inorganic materials in their complex organic together with different heteroatoms (e.g., N, P, or S) [16,24]. However, the quality and quantity of biochar depends on several parameters such as feedstock material and operational conditions.

Biochar can be prepared through different processes such as gasification (where different biochar, gaseous fuel such as syngas, and tar (oil) are produced); torrefaction (where biomass is thermally treated for short period of time at low temperature sally 473-573 K); hydrothermal carbonization (where biochar is produced in presence of water, low

oxygen content, high pressure usually 14-22 MPa and low temperature at 393-573 K); and pyrolysis process (where biomass is thermally converted into its basic components at 473–1473 K in limited or inert atmosphere) [25-27]. **Figure 1** shows the simple overview of biochar production from biomass using different thermochemical processes. Hence, high carbon content and porous biochar is produced due to those processes and their different conditions [28,29] [30].



**Figure 1:** General overview of biochar production from different biomasses.

Owing to unique structure and surface properties of biochar, it can act as an excellent adsorbent for several gases capture. In a study, Mohd, *et al.* [31] reported that adsorption of toxic gases on biochar surface took place mainly through physisorption process. The surface of biochar contains macro and micro pores which acts storage place for gas molecules [31]. **Table-1** shows the CO<sub>2</sub> intake capacity of biochar at 1 bar atmospheric pressure and at two different temperatures. It is clear from the table that, chemically activated biochars prepared from Vine shoots were capable of adsorbing

higher amount of CO<sub>2</sub> (6.08 mmol/g at 1 bar and 273 K), compared to physically activated biochar (4.07 mmol/g at 1 bar and 273 K) [32,33]. In another study, Ello *et al.* [33] prepared biochar and activated with KOH at 1133 K for 1 h from Africa palm shells. They reported higher CO<sub>2</sub> adsorption capacities (6.3 mmol/g at 273K and 4.4 mmol/g at 298 K and 1 bar, respectively). On the other hand, different CO<sub>2</sub> intake capacities were also reported for chemically activated biochars from rice husk (3.71 mmol/g) [34], pine nut shell (5.0 mmol/g) [35], wheat flour (3.48 mmol/g) [36], vine shoots (2.46 mmol/g) [32], coconut shells (4.23 mmol/g) [7], Jujun grass (hydrochar, 4.9 mmol/g) [37], and Camellia Japonica (Hydrochar, 5.0 mmol/g) [37] at 298 K and 1 bar pressure. Moreover, single step pyrolysis and activation of various biomasses to produce biochar and activated biochars were also reported by Serafin *et al.* [38]. They found CO<sub>2</sub> adsorption capacities of pomegranate peels, carrot peels, and fern leaves were 4.00, 4.18 and 4.12 mmol/g at 298 K, respectively; and 6.89, 5.64 and 4.52 mmol/g at 273 K, respectively at 1 bar. Zhang, *et al.* [39] produced amine functional groups doped activated biochar from black locust. They reported CO<sub>2</sub> adsorption capacity 5.05 mmol/g at 298 K and 1 bar. Similarly, Rouzitalab, *et al.* [40] used urea to synthesis amine functionalized activated biochar from walnut shell in the presence of KOH, and they observed record CO<sub>2</sub> adsorption capacity (7.42 mmol/g) at 298 K and 1 bar.

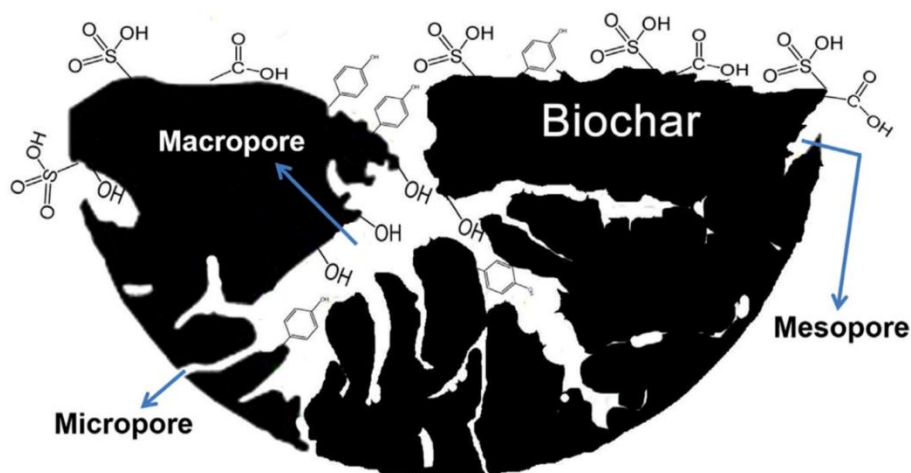
**Table-1:** CO<sub>2</sub> capture performances by top performance biochar produced from different biomasses and at different conditions. Surface area is based on Brunauer-Emmett-Teller



(BET).

Biochar derived from	BET Surface area (m <sup>2</sup> /g)	Pressure (bar)	Adsorption capacity (mmol/g) at 273 K	Adsorption capacity (mmol/g) at 298 K	Source
Vine shoots	767	1	4.07	1.58	[32]
Vine shoots	1305	1	6.04	2.46	[32]
Vine shoots	1439	1	6.08	1.98	[33]
African palm shells	1250	1	6.3	4.4	[33]
Rice husk	2695	1	6.24	3.71	[34]
Pine nut shells	1486	1	7.7	5.00	[35]
Wheat flour	1438	1	5.70	3.48	[36]
Coconut Shells	1172	1	6.04	4.23	[7]
Jujun grass	1512	1	-	4.9	[37]
Jujun grass	3144	1	-	4.1	[37]
Camellia Japonica	1353	1	-	5.0	[37]
Camellia Japonica	3537	1	-	2.8	[37]
Pomegranate peels	585	1	6.89	4.00	[38]
Carrot peels	1379	1	5.64	4.18	[38]
Fern leaves	1593	1	4.52	4.12	[38]
Black Locust	2511	1	-	5.05	[39]
Walnut shell	1315	1	-	7.42	[40]
Pine cone	1680	1	-	4.7	[41]
Saw dust	394.12	1	-	3.7	[42]

However, CO<sub>2</sub> adsorption capacity can significantly vary with the changing of the surface morphology of biochar i.e., the surface area, micropore volume and size together with the effects of temperature and pressure [30,38]. For example, Deng, *et al.* [35] reported that biochar having pore size of 0.33–0.63 nm played an important role for the higher CO<sub>2</sub> adsorption capacity (5.0 mmol/g) at 298 K and 1 bar. It was reported that the control of micropores has greater importance for absorbing high CO<sub>2</sub> compared to surface area and total pore volume [35,38]. **Figure 2** shows the presence of functional groups and porous structures (mesoporosity and microporosity) of biochar materials.



**Figure 2:** Morphology and the presence of functional groups in biochar. Reproduced with permission from [30]; Elsevier and Copyright Clearance Center, 2017.

Therefore, it can be summarized that biochar and activated biochar are promising materials for the adsorption of CO<sub>2</sub>. However, the production process should be simple, cost efficient, and eco-friendly to develop highly efficient CO<sub>2</sub> adsorbents. In addition, new type of modified biochar should keep continue to develop with larger surface area,

well-defined porosity together with surface functional groups, and it is also necessary to produce biochar from low cost materials such as agricultural wastes.

## 2.2. Graphene, Graphene Oxide and CNTs for CO<sub>2</sub> Capture

CBMs can be dimensions less and less than 100 nm, but in many forms. Nanomaterials are extensively using for different applications owing to their downsized unique properties. They can be used as catalysts supports, adsorption, energy conversion, charge storage device preparation, filtration, electrode materials, conductive materials and so many. Graphene based nanomaterials were also used for CO<sub>2</sub> capture [43]. Graphene based materials such as graphene oxide has different oxygen containing functional groups, which can show higher chemical reactivity over pristine graphene [44]. Introduction of different hetero atoms (e.g., N, boron B, aluminum Al, sulphur S and so on) in graphene can increase the CO<sub>2</sub> adsorption capacity. For example, Liu, *et al.* [45] prepared N and B doped graphene aerogels which showed CO<sub>2</sub> capture capacities of 2.9 mmol/g at 273 K and 1.0 bar pressure. On the other hand, Bhanja, *et al.* [46] did a modification of graphene oxide with 2,6-diformyl-4-methyl phenol. They reported that this material could capture CO<sub>2</sub> up to 8.10 mmol/g at 273 K. **Table 2** represents the CO<sub>2</sub> performance by graphene, graphene oxide, CNTs and their composite materials. Huang, *et al.* [47] synthesized a hybrid composite based on polyethyleneimine (PEI) modified graphene oxide and ZIF-8. This composite showed a higher CO<sub>2</sub> capture capacity of 8.08 mmol/g at 273 K at 1 bar. Carbon composites were shown to be efficient in the capture of

CO<sub>2</sub> from flue gas [48]. Rahimi *et al.* synthesized bundles of double-walled CNTs with inner diameter of 8 nm, and they mentioned that they had excellent CO<sub>2</sub> adsorption capacity (3.5 mmol/g at 308 K at 1 bar) [49]. An improved innovative hydrate-based CO<sub>2</sub> capture was observed by the rational surface modification of CNTs by Zhao, *et al.* [50]. An increased CO<sub>2</sub> capture performance (up to 8.75 mmol/g at 196 K at 1 bar) was observed by Jonathan, *et al.* [51] by synthesizing a new composite based on SWCNT (SWCNT@HKUST-1).

**Table 2:** CO<sub>2</sub> capture performances by of recently reported by graphene, graphene oxide, CNTs and their composites.

Adsorbent	BET surface area (m <sup>2</sup> /g)	Pressure (bar)	Adsorption capacity (mmol/g) at 273 K	Adsorption capacity (mmol/g) at 298 K	Source
Reduced graphene oxide	1300	1	3.35	2.45	[43]
BN-Graphene	170	1	2.9	2.6	[45]
Imine-functionalized graphene oxide	190	2	8.1	2.1	[46]
N-functionalized Graphene	979	1	5.8	2.7	[52]
Polyetheleneimine (PEI) modified graphene oxide	29	1	-	2.0	[53]
PEI-graphene oxide@ZIF-8	190	1	8.08	-	[47]
DWCNTs	423	1	-	3.5 (308.00)	[49]
PEI-purine-CNTs		1	-	3.9 (323.00)	[54]
PEI-CNT aerogels	62	1	-	3.3 (343.00)	[55]
SWCNT@HKUST-1	1714	1	-	8.75 (196.00)	[51]
Chitosan-Polybenzoxazine nanocomposite aerogels	710	1	6.70	5.72	[56]

On the other hand, Alhwaige, *et al.* [57] synthesized chitosan aerogels with graphene oxide nanosheets, which showed CO<sub>2</sub> capture capability up to 4.14 mmol/g. Few other aerogels and cross-linked composites have been also reported, which showed excellent up to 5.72 mmol/g at 298 K and 1 bar CO<sub>2</sub> adsorption capacity [56].

Therefore, based on the above description it can be clearly say that graphene, graphene oxide and CNTs have CO<sub>2</sub> capture ability. However, maximum adsorption capacity came from polyethyleneimine based modified graphene and graphene oxide compared to other graphene, graphene oxides and CNTs. Henceforth, future application of such kinds of materials for CO<sub>2</sub> capture need further consideration, but these materials need significant improvement in the adsorption capacity as well as the cost of these materials production.

### 2.3. Activated Carbons for CO<sub>2</sub> Capture

Perhaps, ACs have widely been used for CO<sub>2</sub> capture compared to other types of CBMs. This is due to the fact that they have high SA, pore volume and submicroscopic pores [3,58,59]. ACs are not degraded in acidic and basic conditions [60]. Hence, they possess excellent performance in CO<sub>2</sub> uptake. **Table 3** summarizes the CO<sub>2</sub> capture performances by different ACs.

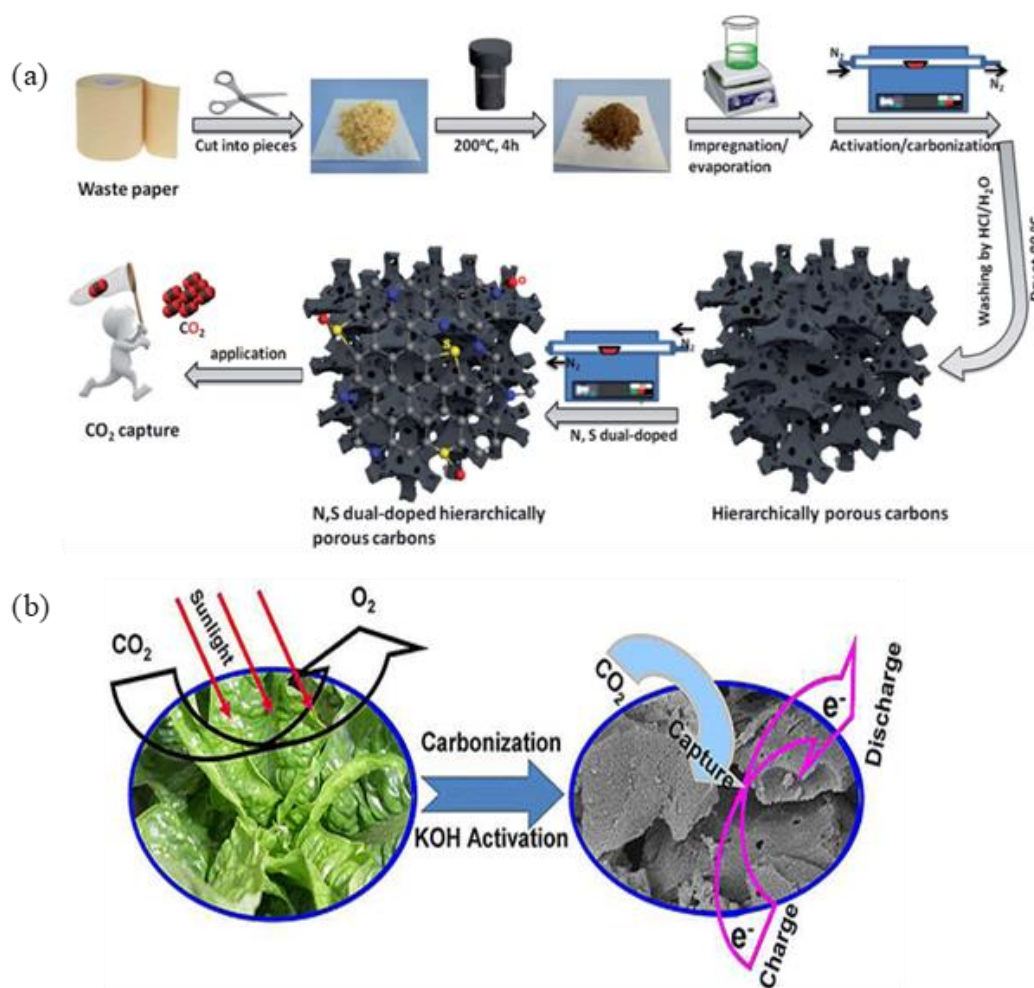
**Table 3:** CO<sub>2</sub> capture performances by different ACs.

Adsorbent	BET surface area (m <sup>2</sup> /g)	Pressure (bar)	Adsorption capacity (mmol/g) at 273 K	Adsorption capacity (mmol/g) at 298 K	Source
AC	3537	18	-	20.66	[61]

AC	1535	1	7.0	4.80	[62]
AC	3350	1	4.4	3.4	[63]
N & S doped ACs	2040	1	7.76	5.19	[64]
Celtuce leaves derived AC	3404	1	6.04	4.36	[65]
Longan shells derived AC	3260	1	5.60	4.30	[66]
Slash pine derived AC	906	1	4.93	3.86 (288.00)	[67]
Coconut shell derived AC	1327	1	5.60	3.90	[68]
Black locust derived AC	2511	1	5.86	3.75	[69]
Starch & cellulose, sawdust	1260	1	6.10	4.8	[70]
Empty fruit bunch derived AC	1720	1	5.22	3.70	[71]
Lignin derived AC	3500	1	8.2	4.8	[72]
Pitch based N- doped AC	1505	1	7.10	4.58	[73]

Different precursors are used for ACs production. However, mostly used precursors are biomasses, coal and petroleum pitch [74]. Shao, *et al.* synthesized ACs from coal tar pitch with extremely high surface area of 3537 m<sup>2</sup>/g. This AC could capture CO<sub>2</sub> up to 20.66 mmol/g at 298 K and 18 bar [61]. On the other hand, ACs can also be prepared from different biomass precursors. For instance, Chen, *et al.* [62] synthesized N-doped microporous-ACs from coconut shells by using urea as activating agent. They found the CO<sub>2</sub> capture capacity of 7.0 and 4.8 mmol/g at 273 and 298 K, respectively at 1 bar. An ultrahigh-surface area of ACs (3350 m<sup>2</sup>/g) were achieved by using starch as a source of precursor. This ACs could capture CO<sub>2</sub> up to 3.4 mmol/g at 298 K and 1 bar [63]. It is reported that around 140 billion metric tons of biomasses are produced each year from agriculture resources [64]. So proper utilization of agricultural wastes together with other

biomass sources such as food residues, nut shells, cellulose craft, lignin, sawdust, rice husk, chips, logs, wood processing residues, marine macroalgae and pitch for the production of ACs in an environmental friendly as well as economic way could be an alternative solution. Such an example is given in the **Figure 3**, where celtuce leaves were pyrolysed at a high temperature followed by a chemical activation process [65].



**Figure 3:** ACs preparation from (a) waste paper, and (b) biomass [64,65]. Reproduced with permissions from the references of [64,65]; Copyright © 2019, Royal Society of Chemistry and Copyright © 2012, American Chemical Society; respectively.

In summary, it can be mentioned that ACs materials are excellent materials for the adsorption of CO<sub>2</sub> with higher adsorption capacity as well as they can be prepared from low cost materials. ACs have higher potential for commercial application as they have higher adsorption capacity, high surface area, microporosity, mesoporosity and stability. Hence, AC is one of the top performance CBMs for the CO<sub>2</sub> capture.

#### ***2.4. Microporous, Mesoporous and Hierarchical Porous Carbons for CO<sub>2</sub> Capture***

Porous carbon materials have versatile properties such as high BET surface area, adjustable pore structure, cost effective and easy regeneration which have proved special attention for CO<sub>2</sub> adsorption [75]. Generally, there are three different types of porous carbon materials i.e. microporous (<2 nm), mesoporous (2–50 nm), and macroporous (>50 nm), but hierarchical porous carbon (HPC) consists all of these properties [76]. Lizen, *et al.* [77] synthesized super porous carbon materials with 95% mesoporosity using polypyrrole as precursor material. They mentioned about ultra-high surface area (2800–4000 m<sup>2</sup>/g) and pore volume (2.5–3.6 cm<sup>3</sup>/g). However, their CO<sub>2</sub> capture capacity was found to be 2.8 mmol/g at 298 K. On the other hand, it was found that the mesoporosity was significantly increased by using sodium amide (NaNH<sub>2</sub>) during activation and doping with magnesium (Mg) and nitrogen (N<sub>2</sub>). These material showed excellent CO<sub>2</sub> uptake performance (3.68–6.31 mmol/g at 273 K) [78–80]. On the other hand, Park, *et al.* [81] synthesized 3D ordered mesoporous carbon, and observed the CO<sub>2</sub> capture capacity (5.53 mmol/g). Recently, a newly designed porous geopolymer template is developed by Pei



*et. al.* [82], which was based on metakaolin, and it had excellent CO<sub>2</sub> capture performance of 26.30 mmol/g at 273 K and 30 bar (**Table 4**). HPC ordered materials have great potential for high CO<sub>2</sub> capture as they have great interest due to their many advantages such as high microporosity, high surface area, higher microporous quantity and so on. For example, HPC with prominent BET surface area up to 2734 m<sup>2</sup>/g had higher CO<sub>2</sub> capture performance up to 27 mmol/g at 30 bar and 300 K [83]. Hence, carbon nanomaterials can possess a hierarchical porous structure and contain both macropores and micropores structure. These properties of carbon together with high surface area are very important for higher CO<sub>2</sub> capture [84].

**Table 4:** CO<sub>2</sub> capture performances by microporous, mesoporous and hierarchical porous carbons.

Adsorbent	BET surface area (m <sup>2</sup> /g)	Pressure (bar)	Adsorption capacity (mmol/g) at 273 K	Adsorption capacity (mmol/g) at 298 K	Source
Mesoporous carbon	3934	1	-	2.8	[77]
NaNH <sub>2</sub> activated Mesoporous carbon	3325	1	6.31	3.66	[78]
Mg & N-doped mesoporous carbon	541	1	3.68	-	[79]
N-doped mesoporous carbon	984.91			4.23 (303.00)	[80]
Ordered mesoporous carbon nitrides	232	30	5.63		[81]

Ordered mesoporous carbon	2255	1	3.0	2.1	[85]
Ultramicroporous carbon	882	1	5.91	4.30	[86]
Mesoporous carbon nanospheres	1240	1	4.76	2.36	[87]
Microporous carbon	1551	30	26.30	-	[82]
N-doped microporous carbon	664	1	5.0	4.0	[88]
Ultramicroporous carbon	1059	1	5.87	3.82	[89]
Microporous carbon aerogel	1871	1	-	3.0	[90]
N-doped microporous carbon	1060	1	-	4.24	[91]
Microporous carbon beads	1755		6.15	4.25	[92]
N-doped microporous carbon	1381	1	5.91	3.86	[93]
Ultra microporous carbon	335	1	-	1.82 (303.00)	[94]
S-doped microporous carbon	1567	1	-	4.5	[95]
N-doped porous carbon	467	1	-	3.13	[96]
Ultra microporous carbon nanoplates	800	1	-	5.2	[97]
Yeast-based porous carbon	1348	1	-	5.0	[98]
Sponge like porous carbon	1143	1	5.6	4.0	[99]

Hierarchical porous carbon	2734	30	-	27 (300.00)	[83]
Hierarchical Porous carbon nitride	550	1	-	2.9	[100]
Hierarchical Porous carbon	2698	1	-	3.7	[101]
Hierarchical nanosheet	1555.7	1	4.62	3.10	[102]
N-doped hierarchical porous carbon	1455.1	1	6.22	4.05	[103]
Waste wool derived N-doped hierarchical porous carbon	1352	1	3.72	2.78	[104]

Although microporous and mesoporous content was found to be the best indicator of CO<sub>2</sub> capture performance, a large pore volume values originating from a distinct large mesoporous peak can improve CO<sub>2</sub> performance as well. So, utilizing the hierarchical porous carbon materials by adjusting various templates and catalysis with large pore volume and high surface area due to good microporous content, would be the best candidate for reducing the emission of CO<sub>2</sub> to the environment.

### 3. Comparative Analysis of CBMs Performances

CBMs are found to be very effective in the capture of CO<sub>2</sub> at various conditions with varying degree of adsorption capacity. We know that different adsorbents have been produced at different conditions using different precursors. Based on rough estimation,

it can mention that biochar and activated biochar are cheap materials compared to any other CBMS. **Table 5** is listed the rough lower and higher price of each CBMs, although actual cost may vary depending on the several factors such as purity, quality, quantity and so on. Based on the table, it can be seen that carbon based nanomaterials such as graphene, graphene oxide and CNTs have higher cost compared to other types of CBMs. In addition, the further modification of those materials can significantly increase the cost such as composite materials preparation and fabrication for the end use. However, their average CO<sub>2</sub> adsorption capacity values (5.13±1.62; 3.23±1.13 mmol/g, respectively at 273 and 298 K) even lower than that of cheap materials such as biochar at both temperatures i.e., 273 and 298 K (**Figure 4**).

**Table 5:** Rough prices of different carbon based adsorbents [105]. Price varies based on purity, quantity, quality and type of materials.

Adsorbents	Lower price (\$/kg)	Higher price (\$/kg)
Biochar/ activated biochar	0.4	0.90
Activated carbons	2.90	8.20
CNTs	1000	10000
Graphene	50	200
Graphene oxide	200	400

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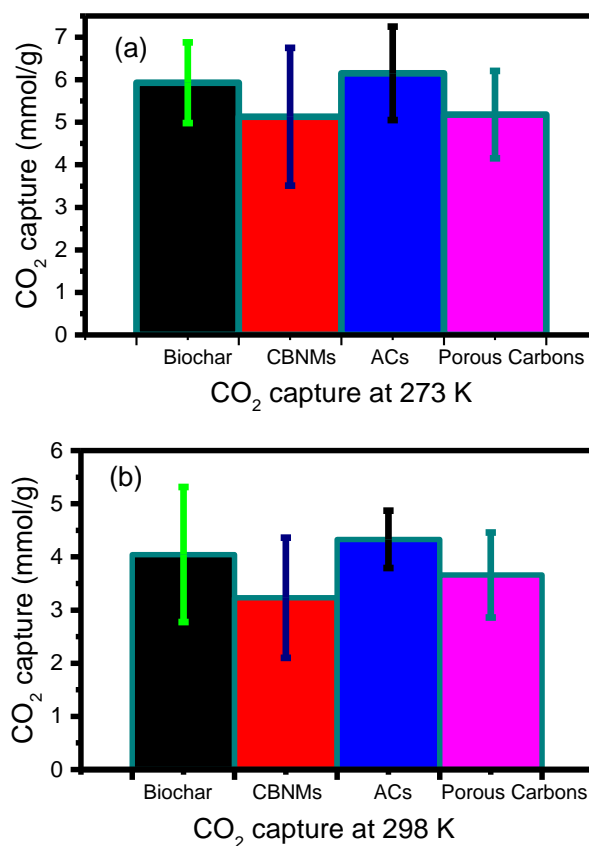
 Other carbons

Depends on processing

Depends on processing

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On the other hand, biochar and activated biochar had higher CO<sub>2</sub> capture performance over graphene, graphene oxides and CNTs although some special case can cease this estimation. On the right side, different meso-micro and hierarchical porous carbons had slightly lower CO<sub>2</sub> adsorption capacities than that of biochar, they have higher efficacy over graphene, graphene oxides and CNTs.



**Figure 4:** Average (with standard deviation) CO<sub>2</sub> capture performance by different carbon based materials at two different temperatures i.e., 273 K and 298 K, respectively.

Biochar refers for biochar and activated biochar; CBNMs refers for graphene-graphene oxide-CNTs and their composites; and porous carbon refers for micro-meso-and hierarchical porous carbons. Each set of data refers to the average value (with standard deviation) at least top ten reported adsorption capacities.

However, ACs have been found very effective among all types of CBMs with higher average CO<sub>2</sub> capture performances (6.15±1.10; 4.33±0.54 mmol/g, respectively at 273 and 298 K) at both temperatures (Figure 4). Therefore, ACs are the top performance materials for CO<sub>2</sub> capture. Anyway, there might have some other form of carbons which can overcome these estimations but grossly ACs are the highly efficient materials for CO<sub>2</sub> capture. Hence, for CO<sub>2</sub> capture, CBMs follow the order of carbon nanomaterials (i.e., graphene, graphene oxides, CNTs and their composites) < meso-micro or hierarchical porous carbons < biochar and activated biochar < activated carbons.

#### **4. Future Challenges and Opportunities**

Although enough progresses have been done of CBMs synthesis and application for CO<sub>2</sub> capture, still there are some lack of those studies. Therefore, further investigations are needed in many areas. They are:

- i. Development of novel composite to improve the CO<sub>2</sub> capture performance of CBMs.

- ii. Need to proper understating of CO<sub>2</sub> interactions with CBMs. For this reason, new analytical tools are needed to develop.
- iii. Ensuring the regeneration efficiency for repeatable applications. Regeneration mechanisms also need to study in details.
- iv. Development of new technologies for efficient capture of CO<sub>2</sub>.
- v. Highly efficient carbon based catalyst needs to develop for the conversion of CO<sub>2</sub> into valuable fuels such as methane.
- vi. Low cost materials with high adsorption capacity need to develop.

## 5. Conclusions

CBMs are very efficient in the capture of CO<sub>2</sub> due to their specific properties including high surface area, mesoporosity, microporosity, micropore volume, well defined pore size distributions and high stability at different environmental conditions. Among different CBMs, activated carbons and activated biochar were found to be the top performance materials for the capture of CO<sub>2</sub> in an environmental friendly way. Although, extensive research has been carried out for the development of different suitable carbon based materials for CO<sub>2</sub> capture, but still there are lack of research for future studies on the development of low cost suitable adsorbent materials.

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