Carbon Dioxide Capture By Biopolymer-Derived Porous Materials

Subjects: Polymer Science

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Rising atmospheric carbon dioxide (CO_2) concentration in the atmosphere is responsible for global warming which in turn causes abrupt climate change and consequently poses a threat to the living organisms in the coming years. CO_2 capture and separation are crucial to reduce the CO_2 content in the atmosphere. Post-combustion capture is one of the most useful techniques for capturing CO_2 due to its practicality and ease of use. For adsorption-driven post-combustion CO_2 capture, sorbents with large surface area, high volume, and narrow pores are highly effective. Natural polymers, such as polysaccharides, are less expensive, more plentiful, and can be modified by a variety of methods to produce porous materials and thus can be effectively utilized for CO_2 capture. A significant amount of research activities has already been established in this field, especially in the last ten years and are still in progress. In this review, we have introduced the latest developments to the readers about synthetic techniques, post-synthetic modifications and CO_2 capture capacities of various biopolymer-based materials published in the last five years (2018–2022).

Carbon dioxide Post-combustion Biopolymers Polysaccharides Cellulose

1. Introduction

Elevation of carbon dioxide (CO_2) gas concentration in the atmosphere is the major factor contributing to global warming. In recent years, CO_2 emissions reached a record level, primarily as a result of the burning of fossil fuels [1]. Carbon capture and storage/sequestration (CCS) is crucial in order to prevent the atmosphere's CO_2 concentration from rising. Pre-combustion, post-combustion, oxy-fuel combustion, and direct air capture are the main methods used to capture CO_2. Out of these methods, post-combustion capture of CO_2 is operationally simple and useful in many industries and power sectors, such as coal-fired power plants [2]. An efficient technique for post-combustion CO_2 capture is the adsorption of gas onto the surface of solid sorbent. Polymers and polymer-based materials are discovered to be particularly promising among several forms of solid sorbents. An efficient and very sustainable method of CO_2 capture is the use of non-toxic, affordable, and widely available polysaccharide-based biopolymers. Porous materials used in CO_2 capture are usually prepared by carbonization and physical or chemical activation of the chosen biopolymers [3].

Since CCS is an important and cutting-edge field of study, a huge number of research articles have been published in the past two decades. Worldwide, there has been a tremendous increase in the development of novel porous materials [3-6]. In this scenario, a comprehensive report is needed to inform the readers of the most recent advancements on the development of new biopolymer-derived materials and their applications in CCS. We have compiled the synthetic methods, post-synthetic changes, and CO_2 capture capacities of various biopolymer-based materials published in the recent five years (2018-2022). We also briefly touched on the factors that affect the selectivity and capacity of CO_2 capture.

2. Types of Biopolymers and Mechanism of Adsorption of CO_2

In the capture and storage of CO_2, both natural and synthetic polymers are widely used. Polysaccharides that have proven to be highly useful in CO_2 capture and storage applications include cellulose, chitosan, lignin, and cyclodextrins. Porous materials derived from polysaccharides capture CO_2 gas by adsorption on the surface. Physical adsorption, also known as physisorption, and chemical adsorption, known as chemisorption, are the two types of adsorption processes. Through non-covalent interactions (Coulombic, Van der Waals, etc.), physisorption takes place on the adsorbent's surface. In this instance, desorption of the gas molecules is a low-energy process. Adsorbents can be reused repeatedly, which is a key benefit of physisorption. On the other hand, reduced selectivity and a low adsorption capacity of the adsorbent at high temperatures are disadvantages. In chemisorptions, gas molecules and the surface of the adsorbent create covalent bonds. On the surface of common adsorbents, there are basic functional groups like amine. Basic functional groups react with acidic CO_2 molecules to produce salts. High adsorption capacity and superior selectivity of the adsorbents are chemisorption's main benefits. This process often has energy-intensive sorbent regeneration as a downside [7].

Isosteric heat of adsorption (Q_{st}) value, calculated by fitting adsorption isotherms by using the Clausius–Clapeyron equation, indicates strength of interaction between adsorbents and CO_2 molecules. A low Q_{st} value points to a predominance of physisorption, whereas a high Q_{st} value points to a strong interaction between the surface of the material and the gas molecules, resulting to a predominance of chemisorption. Effective separation requires good adsorbents to preferentially absorb CO_2 over all other gases. CO_2/N_2 selectivity is thus a crucial indicator for CO_2 capture by adsorbents. Henry's law and the ideal adsorption solution theory (IAST) are used to compute the CO_2/N_2 selectivity. Additionally significant elements that influence adsorption efficacy are the adsorbents' porosity and surface area. The Brunauer-Emmett-Teller (BET) theory is commonly used to assess the surface areas of the adsorbents [8].

3. Polysaccharide-Based Biopolymers for CO_2 Capture

Over years biopolymers are utilized for designing biomaterials for various applications such as packaging materials in the food industry, fuel cells, drug delivery, membrane and medical implants organ preparation, tissue engineering and many more [9–14]. Polysaccharides are cheap and abundant carbohydrate-based biopolymers which has multiple applications [3,15–22]. In studies of CO_2 capture and storage, cellulose, chitosan, lignin, and cyclodextrins are some of the most often used polysaccharides due to their wide availability, simplicity of processing, tolerance to structural modifications, and solubility [3]. The following is a summary of applications of these four key types of biopolymers in CCS that have been documented over the last five years.

3.1. Cellulose-Based Materials for CO_2 Capture

Cellulose is a linear polysaccharide consisting of repeated D-glucose units with the formula of $(C_6H_{10}O_5)_n$. In a recent study, bottom-up ecosystem simulation is coupled with models of cellulosic biofuel production, carbon capture and storage to track ecosystem and supply chain carbon flows for current and future biofuel systems. This approach could have climate mitigation and stabilization potential [20]. Different types of polysaccharides for CO_2 capture have been reported by Qaroush et al, describing the reversible reaction between cellulose and CO_2, their subsequent dissolution, regeneration and CO_2 capturing using functionalised cellulosic materials [3]. One interesting approach for CO_2 capture is converting cellulose to sustainable porous carbon materials [21]. Porous carbonaceous materials are usually prepared by carbonization and activation [21]. Carbonization process can be of two types, (i) pyrolytic approach which involves heating the sample at elevated temperatures of 400–1000 °C in an inert atmosphere (e.g., N_2, Ar). Several steps included in pyrolytic approach like dehydration, condensation and isomerization, which ultimately eliminates most of the hydrogen and oxygen atoms to form H_2O, H_2, CH_4, and CO gases. Other approach (ii) Hydrothermal carbonization (HTC) is usually performed at moderate temperatures (<300 °C) and advantageous due to reduced energy consumption, sample does not need to be dry and gives carbon-rich hydrochars in high yields. Thus in recent times, the HTC method is considered an energy-saving and environmentally friendly approach for carbonization [21]. Two activation methods are being reported which produce porous carbons with large differences in porosity. In general, physical activation processes create porous carbons with moderate surface areas (1000 m^2/g) and narrow micropores that can be beneficial for, e.g., CO_2/N_2 and CO_2/CH_4 separation [21]. In contrast, chemical activation significantly increases the surface area (up to >3000 m^2/g) and pore volume of the porous carbons which can be useful for gas storage [21]. Here CO_2 adsorption capacity of some cellulose-derived materials derived by the carbonization process are discussed. A series of porous carbons derived from commercial cellulose fibres in three steps has been reported by Heo et al. They described that steam molecules played a key role in the pore-opening process and increase in the surface area of the porous carbon materials formed. The cellulose fibres were carbonized under N_2 atmosphere followed by physical activation with steam under gauge pressure. Ultramicropores (pore size < 0.8 nm) resulted by physical activation process significantly contributed to the increase in surface areas from 452 to 540 m^2/g for pre-activated samples to 599–1018 m^2/g for steam-activated samples causing CO_2-over-N_2 adsorption selectivity and increase in CO_2 adsorption capacity by physical adsorption method [22]. In a following study, Zhuo et al. reported a hierarchically porous carbons prepared by carbonization/activation of cellulose aerogels under CO_2 and N_2 atmosphere with improved surface area and volume for CO_2 adsorption. They showed that steam activation is an efficient process to prepare cellulose-based porous carbons with high CO_2 adsorption capacities by physisorption [23].

Chemically activated carbonaceous materials have much higher surface areas thus resulting in much higher CO_2 adsorption capacities. Chemical activation of cellulose by KOH was reported by Sevilla et al. to design microporous carbon materials with a very high surface area of 2370 m^2/g and CO_2 adsorption capacity of 5.8 mmol g^{-1} at 1 bar and 273 K at a high adsorption rate and excellent adsorption recyclability by physisorption mechanism. The material was prepared by hydrothermal carbonization of potato starch, cellulose and eucalyptus sawdust followed by chemical activation using potassium hydroxide [24]. In another study by Xu et al., algae-extracted nanofibrous chemically modified cellulose carbonized under N_2 and CO_2 atmosphere and activated in CO_2 was reported to show significantly higher surface areas (832–1241 m^2/g) and higher volumes of ultramicropores (0.24–0.29 cm^3/g) for CO_2 physisorption [25]. In recent times, cellulose aerogels have also displayed promising applications in carbon storage. A review has been reported by Ho et al. depicting chemical modification of nanocellulose aerogels leading to a large surface area which improved selectivity towards CO_2 chemisorption [26]. Kamran et al. utilized hydrothermal carbonization method and chemical activation with acetic acid as an additive, to develop highly porous carbons. These cellulose-based materials displayed high specific surface area (SSA) (1260–3019 $m^2\ g^{-1}$), microporosity in the range of 0.21–1.13 $cm^3\ g^{-1}$ with CO_2 adsorption uptake of 6.75 mmol g^{-1} and 3.96 mmol g^{-1} at 273 K and 298 K at 1 bar, respectively, and CO_2 selectivity by physisorption mechanism. The carbonaceous material having micropores between 0.68 nm and 1 nm exhibited high CO_2 adsorption potential [27].

However non-carbonized cellulose-derived materials have also been reported for efficient CO_2 adsorption capacities. In this regard, Wang et al. and Sun et al. have reported that cross-linking of nanocellulose enhances the surface area and CO_2 adsorption [28,29]. Amino-functionalization of nanocellulose aerogels although reduced the surface area but still displayed chemisorption of CO_2 with a capacity of more than 2 mmol g^{-1} [26]. In some other reports, cellulose hybrids were designed without any carbonization with inorganic fillers such as silica, zeolite and metal–organic frameworks which improved the surface area and physisorption of CO_2 [26]. Sepahvand et al. have designed nano filters by combining cellulose nanofibers (CNF) and chitosan (CS) at varied loading compositions. Increasing the concentration of modified CNFs increases the adsorption rate of CO_2 and the highest adsorption of CO_2 was showed by 2% modified CNF [30]. In a recent study, epoxy-functionalized polyethyleneimine modified epichlorohydrin-cross-linked cellulose aerogel with rich porous structure and specific surface area in the range of 97.5–149.5 m^2/g has been reported by Chen et al. Good adsorption performance by chemisorption mechanism, with a maximum CO_2 adsorption capacity of 6.45 mmol g^{-1} was displayed by the epoxy functionalized cellulose aerogels[31]. Material type and composition, BET surface area ($m^2\ g^{-1}$), pore size (nm)/total pore volume ($cm^3\ g^{-1}$), mechanism of adsorption, CO_2 capture capacity (mmol g^{-1}) and special features of cellulose-based materials have been tabulated in Table 1.

Table 1. Summary of material type and composition, BET surface area ($m^2\ g^{-1}$), pore size (nm)/total pore volume ($cm^3\ g^{-1}$), CO_2 capture capacity (mmol g^{-1}) and special features of cellulose-based materials.

Material Type and Composition	BET Surface Area ($m^2\ g^{-1}$)	Pore Size (nm)/Total Pore Volume ($cm^3\ g^{-1}$)	CO_2 Capture Capacity (mmol g^{-1})	Special Features	Ref
Porous carbons derived from commercial cellulose fibres	540 and	<0.8 nm–/0.234 and	3.776 at 298 K	CO_2-over-N_2 adsorption selectivity	[22]

	1018	0.429			
Carbonized and activated cellulose from cotton linter	1364	1.42	3.42	-	[23]
Chemically activated cellulose	2200–2400	1.1	4.8	CO_2-over-N_2 adsorption selectivity	[24]
Algae extracted nanofibrous chemically modified cellulose activated in CO_2	832–1241	0.24–0.29	2.29 at 0.15 bar, 5.52 at 1 bar; 273 K	CO_2-over-N_2 adsorption selectivity	[25]
Silica/Cellulose Nanofibril aerogel functionalized with 3-aminopropyl triethoxysilane	11	0.05	2.2 at humid condition	high chemisorption of CO_2 with reduced surface area	[26]
Highly porous cellulose by hydrothermal method and chemical activation using acetic acid as an additive.	1260–3019	0.21–1.13	6.75 at 273 K, 1 bar and 3.96 at 298 K, 1 bar	CO_2 selectivity	[27]
polyethyleneimine-crosslinked cellulose (PCC) aerogel sorbent	234.2	-	2.31 at 25 ℃ under pure dry CO_2 atm	Adsorption-desorption recyclability	[28]
Cellulose nanofiber (CNF) surface was	~360	~4 nm	4.8	Increasing the concentration of	[30]

functionalized using chitosan (CS), poly [β-(1, 4)-2amino-2-deoxy-Dglucose]				modified CNFs increases the adsorption rate of CO_2	
Epoxy-functionalized polyethyleneimine modified epichlorohydrin-cross-linked cellulose aerogel	97.5–149.5	-	6.45	Material showed preferable rigidity and carrying capacity	[31]

One important class of nanocellulose-based materials and their subsequent application involves membrane separation of CO_2. In this regard, Ansaloni et al. reported micro fibrillated cellulose/Lupamin membrane which showed very good CO_2 permeability. However the selectivity of CO_2/N_2 and CO_2/CH_4 (in the order of 500 and 350, respectively, for pure micro cellulose) was compromised thus decreasing the overall membrane performance [32]. Venturi et al. later did a systematic study of CO_2 permeability by nanocellulose-based membranes under the influence of doping. They designed films by blending the commercial Polyvinylamine solution Lupamin® 9095 (BASF) with Nano Fibrillated Cellulose (NFC). It was reported that, increasing water vapour and a higher presence of Lupamin in the film improved CO_2 gas permeability as well as selectivity. NFC content of 70 wt% Lupamin showed a selectivity of 135 for the separation of CO_2/CH_4 and 218 for CO_2/N_2 while the maximum permeability in the order of 187 Barrer was reached at 80% RH [33]. In a follow up study by the same group, the addition of l-arginine to a matrix of carboxymethylated nano-fibrillated cellulose (CMC-NFC) resulted in a mobile carrier facilitated transport membrane for CO_2 separation. l-arginine (45 wt.% loading) greatly improved CO_2 permeability by 7-fold from 29 to 225 Barrer and selectivity with respect to N_2 from 55 to 187 compared to pure carboxymethyl nanocellulose matrix [34]. Pure and mixed matrix membranes (MMMs) with polyethylene glycol (PEG), Multi-walled carbon nanotubes (MWCNTs) and cellulose acetate (CA) has been reported by Hussain et al to capture carbon from natural gas. Membranes of pure CA, CA/PEG blend of different PEG concentrations (5%, 10%, 15%) and CA/PEG/MWCNTs blend of 10% PEG with different MWCNTs concentrations (5%, 10%, 15%) were designed. The CO_2/CH_4 selectivity is enhanced 8 times for pure membranes containing 10% PEG and 14 times for MMMs containing 10% MWCNTs and in mixed gas experiments, the CO_2/CH_4 selectivity is increased 13 times for 10% PEG and 18 times for MMMs with 10% MWCNT [35]. Composite membranes using non-stoichiometric ZIF-62 MOF glass and cellulose acetate (CA) are reported by Mubashir et al. The materials exhibited pore size (7.3 Å) and significant CO_2 adsorption on the unsaturated metal nodes [36]. In more recent studies, another class of mixed matrix membranes (MMMs) are reported by Rehman et al. by incorporating (1–5 wt%) Cu-MOF-GO composites as filler into cellulose acetate (CA) polymer matrix by adopting the solution casting method. They reported 1.79 mmol g^{-1} and 7.98 wt% of CO_2 uptake at 15 bar [37]. Some other foam-like cellulose composites reported by Wang et al with microporous metal–organic frameworks (MOFs) in a mesoporous cellulose template shows high durability during the temperature swing cyclic CO_2 adsorption/desorption process and a high CO_2 adsorption capacity of 1.46 mmol g^{-1} at 25 °C and atmospheric pressure [38].

3.2. Chitosan-Based Materials for CO_2 Capture

Natural biopolymer chitosan (CS) is a marine waste material which is inexpensive, abundantly available, renewable, environmentally friendly and biodegradable polysaccharide and is the second most abundant natural polysaccharide after cellulose [39]. CS may be used in CO_2 adsorption because of its ease of processability, low maintenance and energy necessity. CS chains have a large number of basic amine groups which facilitate adsorption of the acidic CO_2 molecule on the surface of the adsorbents [40,41]. However, pure chitosan suffers from low surface area resulting lower carbon dioxide adsorption. Henceforth, most of the studies reporting chitosan-derived sorbents aim to fabricate the surface properties of CS and maximize the CO_2 adsorption capacity [42]. Hierarchical porous nitrogen-containing activated carbons (N-ACs) were prepared with LiCl-$ZnCl_2$ molten salt as a template derived from cheap chitosan via simple one-step carbonization under Ar atmosphere. The obtained N-ACs with the highest specific surface area of 2025 m^2 g^{-1} and a high nitrogen content of 5.1 wt% were obtained using a low molten salt/chitosan mass ratio (3/1) and moderate calcination temperature (1000 °C). Importantly, using these N-ACs as CO_2 solid-state adsorbents, the maximum CO_2 capture capacities could be up to 7.9/5.6 mmol g^{-1} at 0 °C/25 °C under 1 bar pressure, respectively by physisorption mechanism. These CO_2 capture capacities of N-ACs were the highest compared to reported biomass-derived carbon materials, and these values were also comparable to most of porous carbon materials. The N-ACs also showed good selectivity for CO_2/N_2 separation and excellent recyclability [43]. Chagas et al. reported a green method for CO_2 capture by showing the effects of hydrothermal carbonization (HTC) on chitosan’s chemical properties and its potential. Chitosan’s surfaces and structural properties are modified after HTC which increases the CO_2 adsorption capacity by 4-fold compared to the non-HTC treated chitosan [44]. Acetic acid-mediated chitosan-based porous carbons were developed by Kamaran et al. following a combination of hydrothermal carbonization treatment and chemical activation with KOH and NaOH under a flowing stream of nitrogen. The CO_2 uptake was reported to be 8.36 mmol g^{-1} for KOH samples and 7.38 mmol g^{-1} for the NaOH sample. These synthesized carbon adsorbents also exhibited regenerability after four consecutive adsorption–desorption cycles and also high CO_2 selectivity over N_2 gas [45].

Azharul Islam et al. have reported a non-carbonized chitosan–bleaching earth clay composite (Chi–BE) as an efficient adsorbent for CO_2. They showed that temperature, adsorbent loading and CO_2 concentration exerted significantly positive effects on CO_2 adsorption by Chi–BE within the ranges and levels studied, whereas the interaction of adsorbent loading and CO_2 concentration only affected CO_2 adsorption. The optimum conditions were 38.13 °C, adsorbent loading of 0.72 g and CO_2 concentration of 25%, which produced the adsorption capacity of 7.84 mmol g^{-1} using the desirability function and the composite can also be recycled [46]. Material type and composition, BET surface area (m^2 g^{-1}), pore size (nm)/total pore volume (cm^3 g^{-1}), mechanism of adsorption, CO_2 capture capacity (mmol g^{-1}) and special features of chitosan-based materials have been tabulated in Table 2.

Table 2. Summary of material type and composition, BET surface area (m^2 g^{-1}), pore size (nm)/total pore volume (cm^3 g^{-1}), mechanism of adsorption, CO_2 capture capacity (mmol g^{-1}) and special features of chitosan-based materials.

Material Type and Composition	BET Surface Area (m^2 g^{-1})	Pore Size (nm)/Total Pore Volume (cm^3 g^{-1})	CO_2 Capture Capacity (mmol g^{-1})	Special Features	Ref
N-doped Atcivated carbon from chitosan char by KOH activation	907	0.39	1.86	High CO_2/N_2 selectivity and excellent recyclability	[40]
N-doped carbonized chitosan	849	0.5–1.0 nm, 1.0–1.5 nm and 1.5–2.5 nm with maximum pore volume of 0.68	3.2	Can be used as an electrode material and adsorbent	[41]
Pyrolyzed chitosan– and chitosan-periodic mesoporous organosilica (PMO)– based porous materials	376	~2 nm, 0.346	1.9 at 500 kPa	Best selectivity for CO_2/CH_4 separation at 1.5% (m/v) of chitosan solution dried under supercritical CO_2	[42]
N containing activated carbons (N-ACs) with LiCl-$ZnCl_2$ molten salt as a template derived from cheap chitosan by carbonization.	2025	1.15	7.9 mmol g^{-1} at 0 °C/25 °C, 1 bar	Selectivity for CO_2/N_2 separation, excellent recyclability	[43]

Hydrothermal carbonized (HTC) of chitosan	2	-	0.45	-	[44]
Acetic acid-mediated chitosan-based highly porous carbon adsorbents	4168	1.386	8.36	CO_2 selectivity over N_2	[45]
Chitosan-Bleaching earth	71.26	0.19	7.65	Recyclable	[46]

3.3. Lignin-Based Materials for CO_2 Capture

Lignin is a class of complex organic polymers found in plants particularly important in the formation of cell walls, especially in wood and bark. Chemically, lignins are polymers made by cross-linking phenolic precursors. The synthesis of multiscale carbonized carbon supraparticles (SPs) by soft-templating lignin nano- and microbeads bound with cellulose nanofibrils (CNFs) have been reported by Zhao et al. which were well suited for CO_2 capture (1.75 mmol g^{-1}), while displaying a relatively low pressure drop (~33 kPa·m^{-1} calculated for a packed fixed-bed column). Moreover, the carbon SPs did not require doping with heteroatoms for effective CO_2 uptake and also showed regeneration after multiple adsorption/desorption cycles [47]. Non-carbonized lignin-based materials have been reported by Shao et al. and Liu et al. [48,49]. Lignin depolymerization was done selecting six aromatic units from lignin and O-rich hyper-cross-linked polymers (HCPs) was developed by one-pot Friedel–Crafts alkylation reaction for CO_2 capture. In a recent report, the resins were synthesized from lignin, 4-vinylbenzyl chloride, and divinylbenzene by free radical polymerization reaction followed by Friedel–Crafts reaction which displayed excellent CO_2 capture (1.96 mmol g^{-1}) at 273 K and 1 bar and reusability [49].

3.4. Cyclodextrin-Based Materials for CO_2 Capture

Cyclodextrins are glucopyranosides bound together in various ring sizes renowned for their structural, physical and chemical properties. Due to their unique ability to encapsulate other molecules, they are widely used in industrial applications [50]. The cyclodextrin (CD)/graphene composite aerogel synthesized by hydrothermal carbonized reaction at 80 °C for 18 h exhibits an adsorption capacity of CO_2 at 1.02 mmol g^{-1} [51]. Cyclodextrin-based non-carbonized materials also reported to be efficient CO_2 adsorbent [52–54]. Two isostructural cyclodextrin-based CD-MOFs (CD-MOF-1 and CD-MOF-2) are demonstrated to have an inverse ability to selectively capture CO_2 from C_2H_2 by single-component adsorption isotherms and dynamic breakthrough experiments. These two MOFs exhibit excellent adsorption capacity and selectivity (118.7) for CO_2/C_2H_2 mixture at room temperature [52]. A new solid acid adsorbent for CO_2 capture derived from β-cyclodextrin has been obtained which shows a capacity of 39.87 cm^3/g at 3.5 bar [53]. For thermal activation, a rapid temperature-assisted synthesis has been reported to improve the porous structure of the cyclodextrins for CO_2 adsorption [54]. Another category of cyclodextrin-based materials involves CO_2 adsorption by thermal activation under N_2 atmosphere [55,56].

4. Conclusions

In this review, we have provided an overview of the synthesis, CO_2 capture potential, and key factors influencing the CO_2-philicity of several natural polymer-derived materials that have been described in the literature over the last five years. Despite the relatively low CO_2 capture capabilities of biopolymers, microporous and nanoporous materials made from them showed good adsorption capability. Particularly, membranes made of nanocellulose were discovered to be prospective candidates for the large-scale capture and separation of CO_2 from flue gas. In the study for creating novel materials for post-combustion CO_2 capture and separation, biopolymers have played a significant role. Large-scale CO_2 capture requires solid adsorbents that have strong moisture resistance, large surface area (>1000 m^2/g), abundant micropores, >2 mmol g^{-1} CO_2 adsorption capacity, and >100 CO_2/N_2 selectivity. At the same time, the adsorbent's mass manufacture must be economical.

Using biopolymers to capture CO_2 has made significant progress thus far, but there are still many obstacles to overcome. Surface modification and processability are hampered by many biopolymers' low solubility in common solvents. As a result, creation of membranes, which are very helpful for large-scale CO_2 capture and separation, becomes problematic. Flue gas has a partial pressure of CO_2 as low as 3-15 kPa and a temperature between 80 and 90 °C. Therefore, it is necessary to increase the CO_2 capture capabilities of biopolymer-derived materials at high temperatures and low pressures.

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