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Chemically Activated and Surface-Functionalized Biomass Feedstock for Enhanced CO_2 Capture: A Comprehensive Review

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Abstract

The disposal of CO_2 emissions and biomass waste are major environmental challenges. Chemical activation of biomass to produce activated carbon (AC) has been extensively acknowledged to produce high-performance CO_2 adsorbents. This review provides a comprehensive and critical assessment of biomass resources, various chemical activators to convert biomass to AC with improved surface morphology, and surface functionalizers including ionic liquids (ILs) and green chemicals (GCs) to further modify the surface properties of AC for efficient CO_2 capture. AC is surface functionalized using ILs and GCs, however GCs represent a greener and more sustainable alternate because of their lower environmental risks. The key findings indicated that optimum carbonization and adsorption temperatures as well as activator to biomass ratios are dependent on the nature of biomass, while pressure showed an inverse relation with adsorption capacity. KOH was identified as the most effective chemical activating agent for most of the biomass. Furthermore, ammonium-based functionalizers demonstrated the highest effectiveness in enhancing CO_2 adsorption. Briefly, successful CO_2 adsorption performance arises from the synergistic effects of biomass feedstock properties, optimized activation conditions, and tailored surface chemistry instead of a single material property.

Keywords

biomass conversion, activated carbon, chemical activators, surface functionalization, CO_2 capture

1 Introduction

The inappropriate dumping of biomass waste and excessive CO_2 release have necessitated innovative and practical solutions for worldwide waste management based on the waste-to-wealth approach [1]. Among anthropogenic gases, CO_2 alone has been reported to account for around 74% of the total emissions, and its emission rate is continuously increasing each year [2]. According to a 2023 report by the United Nations Framework Convention on Climate Change (UNFCCC) [3], global temperatures had already risen by approximately 2 °C above pre-industrial levels by 2015, and are projected to increase further in the coming decades without substantial reductions in CO_2 emissions [4].

There are various CO_2 capture technologies including, solvent absorption [5], membrane separation [6], and solid adsorption [7]. Similarly, there are various biomass waste management technologies such as pyrolysis [8], landfilling [9], gasification and incineration [10]. To mitigate the biomass waste and CO_2 simultaneously, biomass conversion into activated carbon (AC) for CO_2 capture has been considered as a promising technique [11]. Among various solid adsorbents, AC synthesized from biomass under optimum operating conditions has been reported as one of the most reliable adsorbents for CO_2 capture because of its high adsorption capacity, easy availability, low raw material cost, excellent regenerability, improved adsorption kinetics, and high thermal stability [7].

As compared to physical and physicochemical activation, chemical activation offers better surface morphology and adsorption properties for AC synthesis [12, 13]. After the production of AC, surface functionalization plays an important role in further enhancing its CO_2 adsorption capability. Pristine AC generally exhibits lower CO_2 adsorption capacity as compared to surface-functionalized AC [14]. AC has been surface-functionalized using

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ionic liquids (ILs) and green chemicals (GCs) to enhance the CO_2 adsorption performance by introducing active sites onto the surface of the adsorbent [15, 16]. Whereas, GCs have been mainly derived from renewable resources or biomass wastes and have minimal environmental impact [17, 18]. Several recent reviews have discussed biomass-derived AC, its chemical activation and surface modification techniques for enhanced CO_2 adsorption. Table 1 represents the significance of this review over latest existing reviews [5, 19, 20].

The current review presents a comprehensive and critical assessment of biomass feedstock selection with its optimization, chemical activation strategies for biomass to produce AC, surface functionalization of AC using ILs and GCs, and effects of carbonization and adsorption parameters. In addition, it critically highlights the key challenges, research gaps, and future research opportunities for the development of sustainable biomass-derived adsorbents for CO_2 capture. Current review addresses this important research gap by integrating these aspects, which have not been comprehensively covered in any previous review articles, to the best of the authors' knowledge.

2 Global importance of biomass activation for CO_2 capture

The bibliographic identification was conducted using the Scopus database [21], focusing on publications from 2021 to 2026. The search strategy employed combinations of the keywords including "Biomass", "Chemical Activation", "Carbon Capture", "Ionic Liquid", and "Green Chemicals", which initially retrieved 5,489 publications. The results were subsequently screened by excluding non-English publications and records that were not relevant to the scope of this review. Furthermore, the search was refined by limiting the subject areas to environmental science, chemical engineering, chemistry, engineering, and materials science, while including both research and review articles. Following the screening process, 4,007 publications were retained for bibliometric analysis. The bibliographic data were subsequently analyzed and visualized using VOSviewer [22] and Microsoft Excel [23] to identify research trends and thematic relationships. These research themes reflect the increasing attention devoted to biomass-derived AC and provide the foundation for the critical discussions of Bioenergy with Carbon Capture Utilization and Storage (BECCS) presented in this review, as highlighted in VOSviewer diagram in Fig. 1.

Fig. 2 presents the global annual land sea surface temperature relative to the pre-industrial period, showing a significant acceleration in global warming, particularly since the 1980s. The consistent rise in global temperature develops the urgent need for efficient CO_2 capture technologies, highlighting the importance of developing sustainable biomass-derived adsorbents as a viable strategy for the mitigation of climate change [24]. Similarly, biomass waste generates nearly 140 gigatons of organic residues annually, with improper disposal contributing up to 18% of emissions, while the biomass recycling market is projected to reach $142.3 billion by 2034 [25]. There are numerous viable biomass sources reported for the production of AC by using chemical activation [5]. The activation of biomass into AC is essential for the sustainable CO_2 capture. This process utilizes renewable biomass waste, thereby reducing environmental impacts. Among the various activation techniques, chemical activation is significantly important, because it increases the surface area and porosity of the AC, which in turn improves CO_2 adsorption, enables lower activation temperatures and energy conservation, while allowing the tailoring of pore structures for selective CO_2 capture [26, 27].

The unique properties of AC, such as low cost, easy availability, high CO_2/N_2 selectivity, low affinity for moisture and impurities, better regenerability, thermal stability, high pore volume, and low heat of adsorption make it a highly desirable adsorbent for purification and separation processes in the industrial applications [28–30].

Table 1 Significance of this review over existing reviews [5, 19, 20]

Features	Existing review	This review
CO_2 capture from surface functionalization of biomass.	Lacks the study of GCs [19].	Presents optimization of biomass feedstock, chemical activation of biomass feedstock to produce AC, its chemical activation, surface functionalization of AC using ILs and GCs, effect of carbonization and adsorption parameters; critical analysis for enhanced CO_2 capture.
Various CO_2 capture technologies.	Limited discussion on effects of biomass activation, adsorption parameters, ILs and GCs [20].	
AC production and surface functionalization for CO_2 capture.	Presents preparation of AC and effect of critical parameters with brief discussion on surface functionalization, lacking analysis of ILs and GCs [5].	

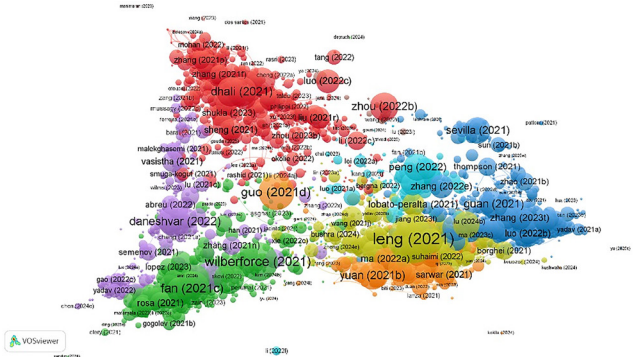


Fig. 1 Bibliographic analysis of the BECCS approach from 2021 to 2026

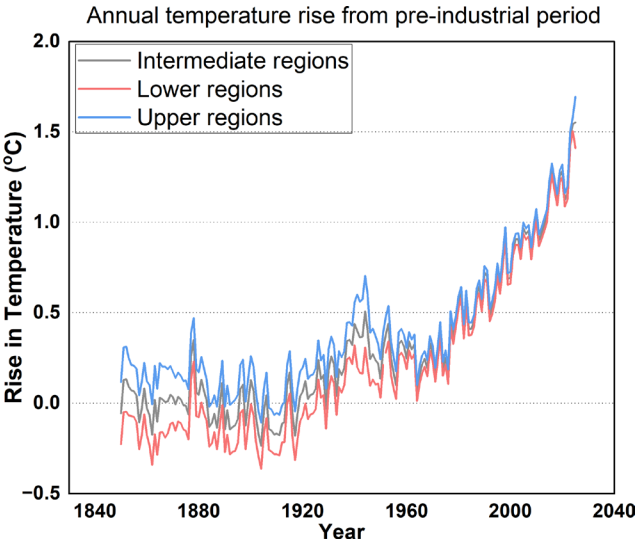


Fig. 2 Annual temperature rise alongside increasing global CO_2 release [24]

The composition of biomass as a raw material significantly influences the physicochemical properties of AC, because of the presence of carbon, sulfur, nitrogen, hydrogen, and oxygen [31]. The initial carbon framework is produced during carbonization, which removes volatile components and develops the primary pore structure. Thereafter, the resulting physicochemical characteristics and CO_2 adsorption performance of AC are dependent on the activating agent, activation process and parameters, impregnation ratio, and post-treatment conditions. As compared to physical or physiochemical activation, chemical activation generally results in higher surface area and microporosity, particularly at lower temperatures, leading to an enhanced CO_2 adsorption performance, although environmental impact, chemical recovery, and scalability must also be considered. Thus, this review focuses on chemical activation because of its reported advantages, while also discussing its drawbacks and future directions [32]. In Section 3, the chemical activation technique, which is considered as one of the most suitable approach has been discussed in detail.

3 Chemical activation of biomass

Chemical activation involves the impregnation of carbon precursors (such as biomass) with a dehydrating agent. There are two types of chemical activation processes, single-stage and two-stage. In single-stage activation, impregnation and carbonization are performed simultaneously in the presence of an activating agent [33]. In contrast, in two-stage activation, the carbon precursor is carbonized first and then in the second step, it undergoes impregnation with the dehydrating agent [34]. In two-stage activation, the development of pores during the first step was observed, which improved the surface chemistry of AC when mixed with the activating agent, whereas in the second step, the AC acquired a well-developed surface area and pore volume [35].

Furthermore, the dehydrating agents, also known as activating agents, can be solid or liquid [36, 37]. Usually, solid-solid mixing results in insufficient impregnation of activating agents, that may lead to an inadequate formation and expansion of pores on the AC surface [38]. However, it depends mainly on the nature of activating agent used. It has been observed that when two activating agents, namely K_2CO_3 and NaOH, both belonging to a basic group, were compared using physical mixing and wet impregnation, K_2CO_3 showed better results with the wet impregnation technique, with the BET surface area of 1106 m^2/g and total pore volume of 0.75 cm^3/g. However, after physical mixing, these properties were diminished and the BET surface area and pore volume were 908 m^2/g and 0.43 cm^3/g, respectively. Conversely, NaOH showed better results with solid-solid physical mixing with the improved BET surface area and pore volume of 994 m^2/g and 0.57 cm^3/g, respectively [39, 40]. It has also been reported that the particle size of the solid activating agent plays a substantial role. Significantly improved BET surface area and pore volume were observed when granular NaOH was replaced by powdered NaOH, because of the better contact and impregnation of the activating agent with the carbon precursor [35].

The activating agents, as mentioned above, react with lignin, hemicellulose, cellulose, or polysaccharides (hydrocarbon composition depends on the biomass type) in the biomass. The activation mechanism depends on the biomass nature, thereby governing pore development [41]. The activating agent affect the resulting surface chemistry. The presence of alcohol, carbonyl, carboxyl, and hydroxyl groups in AC has been observed to provide the active sites for CO_2 adsorption [39, 42–44].

Overall, chemical activation offers significant advantages in enhancing the physicochemical properties and CO_2 adsorption performance of biomass derived ACs, the

activation mechanisms and resulting pore development vary considerably with the types of activating agent and biomass. Therefore, a comprehensive understanding of the selection criteria and reaction mechanisms of various activating agents is essential. The selection criteria have been critically discussed in Sections 3.1 and 3.2.

3.1 Selection of a suitable chemical activator

The selection of a suitable activator mainly depends on the required outcomes of a specific process, such as the required adsorption capacity, adsorption-desorption cycle capability, and environmental conditions [45]. Strong alkalis, acids, and salts as biomass activators contribute to produce AC for CO_2 adsorption, however sometimes weaker ones are effective as well. KOH has been reported to have the highest CO_2 adsorption capacity, however its high pH and corrosiveness impact the soil and water, consequently adversely affecting animal and human life [46]. An appropriate disposal method to avoid the environmental hazards is therefore an ultimate requirement. The activating agents that are less hazardous to environment have been receiving increasing attention [47].

Chemical activation mainly promotes pore development through dehydration, gasification, oxidation, and intercalation reactions, resulting in enhanced surface area and microporosity. Dehydration removes oxygen-containing groups and promotes cross-linking, intercalation facilitates structural rearrangement, gasification removes carbon and develops pores, and oxidation promotes micropore formation by oxidizing the carbon matrix. The chemical activation mechanism in case of various chemical activators has been summarized schematically in Fig. 3.

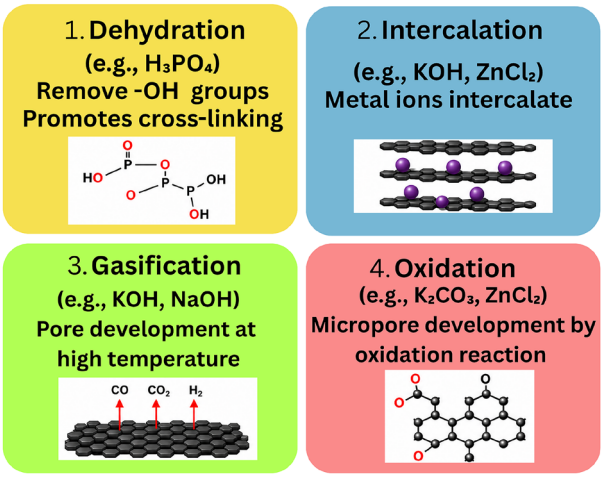


Fig. 3 Mechanisms of chemical activation

Accordingly, adsorption performance is not solely dictated by the type of activating agent or biomass precursor, the synergistic effect of an optimized pore structure and tailored surface chemistry are the important factors as well. Moreover, while selecting an activator, the nature of the biomass, adsorption requirements, and the ability to mitigate its environmental drawbacks are also critical parameters to consider [48, 49].

The selection criteria for appropriate activation parameters to achieve an optimum performance require the evaluation of activation temperature and time, adsorption temperature and pressure, and the activator-to-biomass ratio [45], all of which are described and critically evaluated in Table 2 [48, 50–60]. In conclusion, the effectiveness and selection of a chemical activator is dependent on various factors including its ability to develop the porosity, its compatibility with the biomass precursor, and environmental considerations. Furthermore, optimization of the biomass activation parameters is also crucial for high-performance and sustainable CO_2 adsorption, as discussed in Section 3.2. Section 3.2 provides a concise overview of each activation parameter.

3.2 Optimization of biomass activation

Biomass feedstock is highly viable in terms of its composition and different types of biomass feedstocks even though subjected to the same activation and adsorption conditions, provide different results in terms of CO_2 capture [61]. Effective AC production results from an appropriate pre-treatment, necessary for the formation of an optimum surface area and porous structure for efficient CO_2 adsorption [62]. The type of pre-treatment process varies depending upon the type of biomass [63]. The continuous supply of biomass is also an issue, few biomass are available on the seasonal basis and their seasonal availability require crucial storage conditions to avoid degradation [64]. All these issues need effective handling while developing expeditious CO_2 capture facility.

To optimize the biomass feedstock, pre-treatment related to the specific type of biomass is the first factor that needs to be considered [65]. Secondly, activating agents play a significant role in the surface development of biomass. KOH and NaOH are the well suited as activating agents for agricultural, wood and fruit shell biomass [35, 66]. Whereas, H_3PO_4 and $ZnCl_2$ are associated with the effective activation of lignocellulose biomass, such as fruit peels [67]. K_2CO_3 and KOH mainly differ in their ability to develop the porous structure and

Table 2 Chemical activators of biomass and critical parameters

Biomass	Chemical activator	Activation parameters (Temperature, time) (°C, h)	Adsorption parameters (Temperature, pressure) (°C, bar)	Capacity (mmol/g)	Results from literature	Comments, critical analysis	Reference
Yellow mombin fruit	KOH	500, 3	0, 1	7.13	Higher activation temperatures require shorter activation times. Higher activation temperatures may also result in ruptured pore structures.	At higher activation temperatures pores and surface area become optimum. Exposure to excessively high temperatures, particularly for thermally sensitive adsorbents, may result in ruptured pore structures.	[50]
		700, 3	25, 1	10.5			
Bamboo shell	K_2CO_3	800, --	0, 1	7.52			[51]
Lignin waste	$ZnCl_2$	800, 2	0, 1	4.45			[52]
D-Glucose	KOH	700, 1	0, 1	6.46	The higher CO_2 adsorption capacity was observed at comparatively lower temperatures.	The CO_2 adsorption rate of the carbon precursor increases at lower temperatures because of reduced molecular surface vibrations.	[53]
			25, 1	3.92			
Lotus leaf	$NaNH_2$	500, 1	0, 1	5.18			[54]
			25, 1	3.50			
Walnut shell	KOH	900, 1	25, 1	5.20	An increase in adsorption pressure improves CO_2 adsorption.	Increasing the adsorption pressure increases the CO_2 partial pressure. The adsorbents continue to adsorb CO_2 until the saturation capacity is achieved at the applied pressure.	[55]
			25, 10	13.82			
Peanut shell	K_2CO_3	600, 0.5	0, 25	5.7			[56]
Lotus seed	KOH	800, --	0, 1	6.8			[57]
			0, 30	26.4			
Date sheet	KOH	800, 2	0, 1	6.4			[58]
			0, 40	22			

Biomass	Chemical activator	Activator to biomass impregnation ratio	Capacity (mmol/g)	Results from literature	Comments, critical analysis	Reference
Black lotus	KOH	6:1	2.43	An increase in the activator-to-biomass ratio generally enhances the adsorption capacity up to an optimum level. For example, increasing the ratio of which agent? from 4:1 to 6:1 decreased CO_2 uptake. Similarly, ratios of 2:1, 3:1, and 4:1 of which agent? were reported to be optimum for different biomass feedstocks.	Increasing the activator-to-biomass ratio promotes pore development up to an optimum limit. Beyond this point, the excess activator accumulates within the porous structure of AC, blocking CO_2 adsorption. The optimum activator-to-biomass ratio varies depending on the type of biomass and the activating agent used.	[59]
		2:1	6			
Date seed	KOH	4:1	6.4			[58]
		6:1	5.6			
Arundo donax	KOH	2:1	6.3			[60]
Walnut shell	KOH	3:1	5.4			[55]
Parrotia persica wood	H_3PO_4	3:1	3.02			[48]

"Not given" has been represented as --.

the post-treatment washing stages. K_2CO_3 requires fewer washing stages during post-treatment and sometimes results in inadequate pore development, which leads to lower adsorption capacity [47].

All the analysis on the optimization of biomass feedstock, considering the research gap in the literature concludes that every type of biomass behaves differently, as carbon precursor and differences in the characteristics of the adsorbent cause variations in its surface morphology and adsorption capacity. After selecting the appropriate activating agent according to the type of biomass, experimental calibration to determine the optimum operating conditions is a necessity that cannot be skipped based solely on the literature.

The requirement of the desired product, environmental considerations, and economic concerns draw attention towards exploring the types of activating agents, pre-treatment processes, and activation parameters for every novel combination of biomass and activating agent to achieve an optimum performance. Even if similar biomass-derived carbon sources and activation agents were used, large differences in the CO_2 capture performance have been

reported because of variable parameters. Most of these differences can be explained by variations in biomass composition (cellulose, hemicellulose, lignin, and ash content) and activation conditions (temperature, impregnation ratio, and residence time), which influence pore structure development as well as nature and abundance of surface functional groups [61, 62].

Thus, the variability in reported CO_2 adsorption capacities (as showed in Table 2) demonstrates that biomass activation does not follow a specific protocol. Activation process requires specific optimization of the biomass pre-treatment, selection of a suitable activating agent, and activation conditions, while ensuring environmental and economic feasibility. In addition, KOH has been identified as the most effective chemical activating agent for biomass. Furthermore, the surface modification of the chemically activated biomass using surface functionalization is also an important process for efficient CO_2 adsorption, which will be discussed in Section 4.

4 Surface functionalization of activated carbon

Surface functionalization is referred to as surface modification of a solid so that it can efficiently capture a specific species by introducing the specific functional groups, such as nitrogen and oxygen containing groups. These functional groups enhance the basicity of AC surface and improve its CO_2 capture capability through Lewis acid-base interactions [68]. Adsorbents synthesized from various biomass types are functionalized using various types of ILs and GCs to enhance their adsorption capacities and boost the surface properties of the adsorbents [69]. As CO_2 belongs to the weak Lewis acid family [70], basic functional groups are preferred to enhance their ability to capture CO_2, as a result of the availability of free volume and more active sites [71]. Furthermore, Sections 4.1 and 4.2 provide detailed insights into the use of ILs and GCs for the surface modification of AC.

4.1 Ionic liquids

ILs refers to compounds comprising organic cations bonded with inorganic or organic anions [72]. These are also referred to as molten salts and have low melting points; however, high stability makes them suitable for surface functionalization [73]. The ions in the ILs dissociate in the liquid phase, interact, and improve the surface properties of the adsorbents [74]. ILs, because of their unique and reliable properties, are the center of attention for the surface functionalization of AC [75]. Various types of imidazolium [76], ammonium [77], phosphonium [78], and pyridinium [79] based ILs have been previously used for the surface functionalization of AC. The list of abbreviations of selected ILs is given in Table 3. These ILs and their primary outcomes have been summarized and critically analyzed in Table 4 [15, 80–88]. It has been observed that imidazolium based ILs usually have low solubility and they were unsuitable for high CO_2 adsorption on an industrial scale. In addition, no significant change was observed after changing the cations in several imidazolium based ILs [80, 89]. The imidazolium cation containing fluorine anion also showed unsatisfactory results [80]. Conversely, some imidazolium based ILs including acetate anions [81, 82], showed satisfactory results for CO_2 adsorption at high concentrations. Moreover, pyridinium based ILs showed better results in surface modification because of better nitrogen doping and thermal stability, as compared to imidazolium based ILs. Although fewer publications were available, there is a lack of research on the stability, reactivity, and surface functionalization of pyridinium based ILs. Depending on the combination of the specific cation, anion, and the selection of carbon precursor, imidazolium and pyridinium based ILs have demonstrated beneficial outcomes [90–92].

Ammonium based ILs mainly exhibit superior CO_2 adsorption capacity because of the electrostatic interaction

Table 3 Abbreviations of the ionic liquids

Abbreviation	Ionic liquid
[bmim][PF_6]	1-Butyl-3-methylimidazolium hexafluorophosphate
[bmim][$FeCl_4$]	1-Butyl-3-methylimidazolium tetrachloroferrate
[bmim][Ac]	1-Butyl-3-methylimidazolium acetate
[C_4Py][Tf_2N]	1-Octylpyridinium bis(trifluoromethylsulfonyl) imide
[dmedah]	*N*,*N*-Dimethylethylenediammonium
[emim][Tf_2N]	1-Ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide
[emmim][Tf_2N]	1-Ethyl-2,3-dimethylimidazolium bis(trifluoromethylsulfonyl)imide
[emim][Gly]	1-Ethyl-3-methylimidazolium glycinate
[hmim][BF_4]	1-Hexyl-3-methylimidazolium tetrafluoroborate
[hmim][NTf_2]	1-Hexyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide
[PH_4][TFSI]	Phosphonium bis(trifluoromethanesulfonyl)imide*
P(BVIm)	Poly(bis-vinyl imidazolium)
[TMGL][Lac]	Tetramethylguanidinium lactate*
[vbtma][ala]	Vinylbenzyltrimethylammonium alanate
[vbtma][arg]	Poly(vinylbenzyltrimethylammonium arginate)
[vbtma][lys]	(Vinylbenzyl)trimethylammonium lysine

Table 4 Impact of ionic liquids on the CO_2 adsorption performance of activated carbons

Ionic liquid	Class of IL	Critical analysis	Reference
[bmim][PF_6]	Imidazolium based	Although CO_2 adsorption capacity of [TMGL][Lac] was slightly higher as compared to [bmim][PF_6], it was not suitable for high CO_2 removal because of its low solubility.	[80]
[TMGL][Lac]			
[hmim][BF_4]	Imidazolium based	The presence of [BF_4]− and pore-blocking effect of [hmim][BF_4] decreased CO_2 adsorption capability.	
[bmim][ac]	Imidazolium based	The high reversibility of the IL enables efficient regeneration, improving CO_2 adsorption at higher concentrations.	[81]
P(BVIm)	Imidazolium based	CO_2 adsorption capacity enhanced 2.58 times upon functionalization, with improved microporous properties, reusability, and stability of AC.	[82]
[emim][gly]	Ammonium based	The CO_2 adsorption capacity of functionalized AC was observed to be better as compared to pristine AC. This was because of the increased interaction between CO_2 molecules and the functional groups introduced by this IL.	[83]
[vbtm][ala]	Ammonium based	[vbtma][ala] showed significantly better results as compared to simple polyvinyl chloride (PVC) binders.	[84]
[hmim][NTf_2]	Ammonium based	20 wt.% of poly[vbtma][gly] showed the maximum CO_2 adsorption capacity of 19.91 mmol/g. In addition, further increasing the IL composition more than 20 wt.% blocked the pore volume. Moreover, increasing adsorption pressure had a positive effect on the CO_2 adsorption.	[85]
[vbtma][gly]			
poly[vbtma][gly]			
[bmim][$FeCl_4$]	Ammonium based	[$FeCl_4$]$^-$ stabilized the oxygen atoms of AC. 4.4 mmol/g CO_2 uptake was observed at room temperature, 1 bar.	[86]
[dmedah][propanoate]	Protic	All the ILs showed optimum results with a 20 wt.% composition, except for two multi-functionalized amines, [vbtma][arg] and [vbtma][lys]. AC surface-functionalized with [vbtma][gly] showed the highest adsorption capability because of the additional amine group.	[87]
[dmedah][formate]			
[dmedah][acetate]			
[vbtma][gly]	Amino acid based		
[vbtma][arg]			
[vbtma][lys]			
[PH_4][TFSI]	Phosphonium based	Improved micro-pore volume, CO_2 adsorption capacity, and mass transfer rates have been observed as result of surface functionalization.	[15]
[C_4Py][Tf_2N]	Pyridinium-based	Surface area, total pore volume, and micropore volume were improved. Physisorption and exothermic adsorption behavior were observed and the Langmuir model was the best fit for the adsorption data.	[88]

between cation and anion. They can effectively attract CO_2 during the adsorption process, under the specific operating conditions studied in this work [85, 86]. Ammonium based ILs were the most convenient in terms of high thermal and chemical stability and undergo elimination reactions at high temperatures, instead of decomposing into the oxides, such as phosphonium based ILs. Moreover, these ILs provided a strong basic sites to attract the CO_2, which improves the surface properties of AC for CO_2 capture [93, 94].

Moving forward to the phosphonium based ILs, the presence of phosphonium cations improved the CO_2 selectivity and can be paired with multiple anions to show significant results [15]. Phosphonium based ILs showed the highest thermal stability as compared to several imidazolium and pyridinium based ILs. As compared to nitrogen-based salts, phosphonium based ILs have a low manufacturing cost and the absence of acidic protons provides a strong basic side for the CO_2 capture [78, 93]. However, because of the high polarizability and large ionic radius, they tend to form quaternary salts easily [95]. Furthermore, Fig. 4 illustrates how the physicochemical properties of various ILs dictate the surface functionalization and

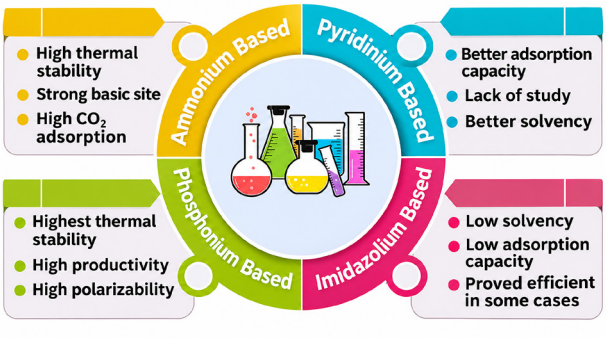


Fig. 4 Selection criteria for ILs

hence CO_2 adsorption performance. Overall, it can be concluded that performance of ILs is governed by the combined effects of cation-anion chemistry and carbon precursor, rather than types of ILs alone. Although, ammonium based ILs generally exhibit superior thermal stability and CO_2 affinity, further research is needed to improve the scalability, stability, and cost-effectiveness of all ILs for practical CO_2 capture applications.

GCs are another environmentally friendly option for the surface functionalization of AC. In Section 4.2, GCs will be discussed for the surface modification of AC.

4.2 Green chemicals

GCs are either organic or derived from biomass. These are less hazardous, biodegradable, environmentally sustainable, and effective alternative chemicals for the surface functionalization of AC, as compared to hazardous chemicals [96, 97]. ILs are highly efficient and sustainable for surface functionalization of AC, however they are costly as well. Some toxicological problems should be considered while dealing with ILs as well [98]. Therefore, as compared to ILs, GCs are environmentally friendly and sustainable.

The composition of GCs used for adsorbent functionalization plays a critical role in determining CO_2 adsorption capacity and selectivity. The incorporation of specific surface functional groups enhances the affinity of adsorbents toward targeted species. Although ammonium and phosphonium rich GCs offer potential for AC modification, their application in CO_2 capture remains relatively unexplored. Most studies involving GC-functionalized biomass derived adsorbents have focused on removing metal ions and wastewater contaminants [99, 100]. For effective CO_2 capture, GCs containing amine or other basic functional groups are particularly promising due to their potential to strengthen CO_2 to adsorbent interactions. For instance, egg white has been investigated as a green functionalizing agent for AC, achieving a CO_2 adsorption capacity of 0.5718 mmol/g at 25 °C and 1 bar [101]. Nevertheless, research on GC functionalized adsorbents for CO_2 capture remains limited, highlighting opportunities to develop environmentally benign surface modification strategies for improving CO_2 adsorption performance.

Fig. 5 summarizes the important properties of GCs for enhancing CO_2 adsorption and illustrates their potential applications as promising green substitutes for surface modification of an adsorbent. In conclusion, GCs offer a sustainable alternative as compared to ILs for AC functionalization. However, their application in CO_2 capture remains highly under-explored. Future studies should focus on tailoring nitrogen rich GCs to achieve an enhanced adsorption performance of AC, while maintaining environmental sustainability.

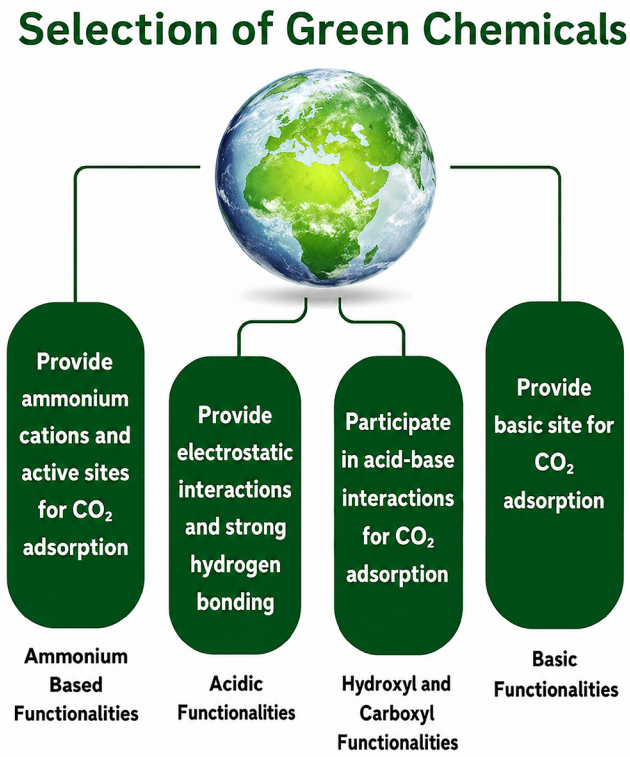


Fig. 5 Functional groups of GCs and their potential role

5 Conclusions and future recommendations

The studies discussed in this review showed that the performance of biomass-derived AC for CO_2 adsorption is influenced by the synergy among various characteristics of biomass precursors, type of chemical activators, activation conditions, and surface functionalization, instead of a single factor. Among the activating agents, the use of KOH resulted in AC with better physical and chemical properties for CO_2 adsorption over a broad range of biomass feedstocks. However, optimum activation conditions depend on the biomass composition, its pre-treatment, activation process and parameters, and the activator-to-biomass ratio.

Additionally, surface modification resulted even higher CO_2 capture capacities by creating active sites on AC surface. Ammonium based ILs were superior in this regard according to available literature, further research is needed in this domain. Conversely, GCs for CO_2 capture have not been fully investigated. GCs are environmentally friendly, however only one study was found in the existing literature to date for surface functionalization of AC related to CO_2 capture. In addition, IL and GC functionalized biomass-derived AC at larger scales is hindered by the regeneration issues, economic limitations, as well as process scale-up

challenges. Therefore, future studies should concentrate on expanding the application of environmentally friendly green chemicals for CO_2 capture and evaluate their long-term regeneration performance and pilot-scale applications to support the practical implementation of sustainable biomass-derived adsorbents for CO_2 capture.

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