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Engineering biomass-derived CO_2 capture materials via hydrothermal processes

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ABSTRACT

Hydrothermal carbonization (HTC) has emerged as a promising technology for converting biomass into high-performance carbon materials, offering potential sustainable solutions for CO_2 capture. HTC operates under moderate conditions to produce hydrochar with enhanced porosity and surface functionality ideally suited for CO_2 sequestration. Recently developed nitrogen-doped and alkali metal-activated hydrochars have improved adsorption capacities, and CO_2 capture capacities up to 320 mg/g, surpassing some traditional materials like zeolites. However, despite its potential to contribute significantly to global efforts seeking to mitigate carbon emissions, HTC faces challenges such as energy consumption and product variability. In this review we explore the fundamental mechanisms of HTC, emphasizing the transformation of wet biomass into porous, carbon-rich materials suitable for adsorption applications. We also discuss the technoeconomic viability of HTC as a scalable and sustainable technology and highlight future research needs aimed at optimizing reaction conditions, synergizing catalysts and solvents, reducing costs, and improving reactor designs that can help pave HTC's role in a low-carbon future.

1. Introduction

The increase of carbon dioxide (CO_2) emissions in the atmosphere has emerged as a pressing global challenge [1]. In 2022 alone, the global CO_2 emissions from fossil fuel combustion soared to an alarming 33,423 million metric tons, exacerbating the impact of climate change and contributing to severe weather events and environmental disruptions [2]. To address this crisis, the Paris Climate Agreement aims to limit global temperature rise to below 2 °C above pre-industrial levels by curbing CO_2 emissions [3]. However, achieving this target is becoming increasingly challenging given the current rise in emissions from human activities.

Although the direct conversion of small amounts of CO_2 into value-added products has been explored, it remains insufficient to address the scale of the problem. A more viable solution is CO_2 capture, utilization, and storage (CCUS), which provides an integrated approach to significantly reduce emissions. This process is particularly valuable in industrial sectors where CO_2 emissions are high, and conversion efficiency remains challenging. By capturing CO_2 at its source and concentrating it from lower to higher concentrations, CCUS enhances the feasibility of subsequent utilization or storage, thereby improving overall conversion rates and contributing to global efforts to mitigate climate change.

There are several pathways for CO_2 capture including post-combustion capture, pre-combustion capture, oxy-fuel combustion, direct air capture, and bioenergy with carbon capture and storage (BECCS). Fig. 1 provides a schematic representation of different techniques for CO_2 capture from industrial flue gas. Pre-combustion capture involves removing CO_2 before fossil fuel combustion by gasifying and reforming the fuel with air and water vapor. This process includes steam reforming to produce CO and H_2, followed by a water-gas shift reaction to convert CO into CO_2 [4]. The CO_2 is then separated and captured, while the resulting H_2 serves as fuel for hydrogen gas turbines. Post-combustion capture, on the other hand, is widely regarded as the most practical and robust technique, as it minimally disrupts existing production mechanisms and is relatively cost-effective. This method typically involves separating CO_2 from flue gases using solvents, which are later regenerated through compression and desorption processes. While the simplicity of retrofitting existing facilities makes this technology appealing, it is

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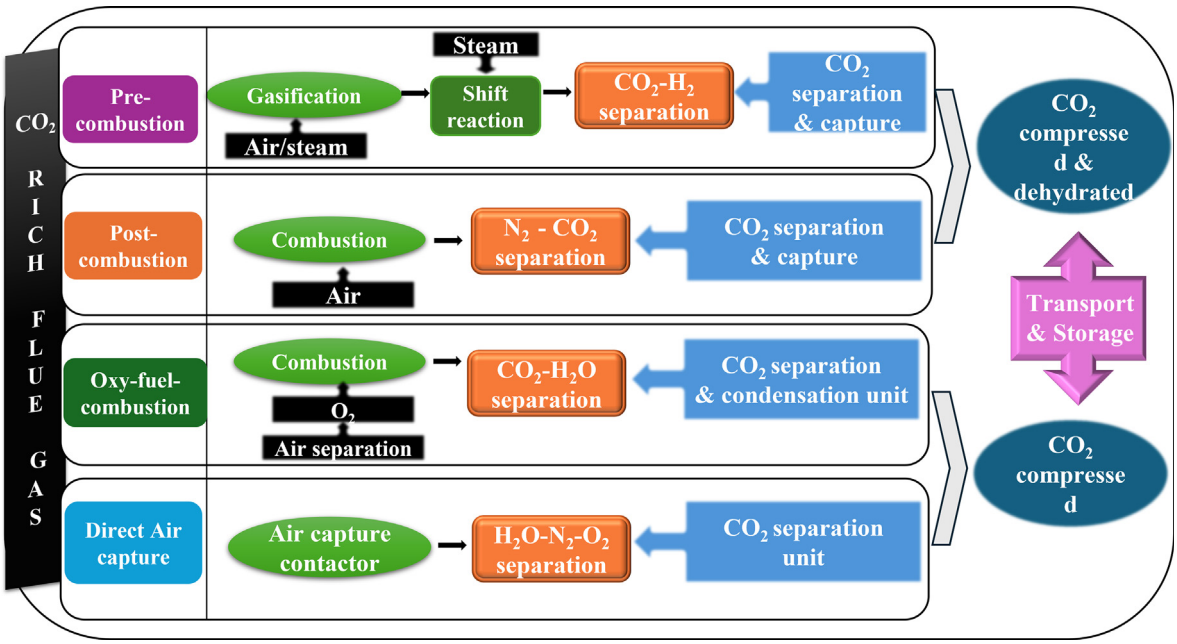

Fig. 1. Representation of various techniques such as pre-combustion, post-combustion, oxy-fuel combustion and direct air capture for CO_2 capture and separation.

highly energy-intensive due to the substantial steam consumption required to regenerate the diluted amine solvent. Given the inherent limitations of current CO_2 capture methods, there is an increasing demand for innovative alternatives. One promising approach is adsorption-based CO_2 capture, which is often preferred over amine absorption due to its lower energy requirements, enhanced selectivity and capacity, and reduced maintenance costs [5–8]. In particular, the development of high-performance biomass-derived adsorbents has increased interest in sustainable and transformative technologies [9]. Biomass, as a renewable and abundant resource, can be converted into carbon-rich adsorbent materials with excellent CO_2 adsorption properties, offering a pathway toward greener and more efficient carbon capture solutions.

The potential of adsorption as a CO_2 capture technology is further enhanced by advancements in material science. Among these promising techniques, hydrothermal processing (HTP) stands out as an environmentally sustainable approach for converting biomass into valuable products, assisting in the reduction of greenhouse gas emissions, improving soil health, and transferring biomass waste from landfills. HTC allow to produce surface-functionalized carbonaceous materials with enhanced porosity and tailored structures for CO_2 capture. For instance, Hao et al. demonstrated that nitrogen-enriched carbon samples exhibited a CO_2 adsorption capacity of 3.13 mmol/g (25 °C, 1 atm) [10]. Similarly, Wahby et al. achieved high surface area carbons through the chemical activation of petroleum pitch, with an exceptional CO_2 adsorption capacity of 4.7 mmol/g at 25 °C and 1 atm outperforming conventional zeolites like 13X and 5A, which absorb approximately 230 mg and 180 mg CO_2/g of sorbent, respectively [11]. These findings clearly indicate that porous carbons with optimized pore structures are highly effective CO_2 adsorbents.

Engineering biomass into surface-functionalized carbonaceous materials with enhanced porosity for CO_2 capture through synergically integrating chemical and physical activation processes would be beneficial given the abundance of raw biomass. This can be achieved via hydrothermal treatments such as pyrolysis, torrefaction, and hydrothermal carbonization, which break down biomass into solid char, liquid oil, and gas, or produce torrefied biomass [12–15]. Among these, hydrothermal carbonization (HTC) stands out as a unique technique that converts wet biomass into highly functional carbonized material without the need for pre-drying. It is considered more sustainable as it processes wet feedstocks directly, reducing energy inputs, minimizing emissions, and enabling the recovery of valuable nutrients. Operating at relatively low temperatures (180–280 °C) with water as the reaction medium, HTC produces hydrochar, a porous and energy-dense material, while emitting minimal gases. The process involves key reactions such as aromatization, dehydration, and hydrolysis; with temperature and reaction time playing crucial roles in the properties of the resulting hydrochar [16–18]. HTC presents a promising pathway for converting biomass into valuable products; however, the high energy consumption, equipment costs, and variability in product quality remain significant hurdles. Fig. 2 illustrates the purpose and potential applications of hydrothermal carbonization in biomass processing.

This review will provide a comprehensive overview of HTC, the structural properties of HTC-derived carbon materials, and their potential applications in CO_2 capture. It also examines the structure-property-application relationships governing these materials and offers perspectives to guide future developments of HTC as a scalable and sustainable biomass conversion technology

2. Hydrothermal dynamics: breakthroughs in processes and formation mechanisms

Hydrothermal carbonization (HTC), first explored in the early 20th century to understand coal formation, continues to be studied for its fundamental mechanisms [19]. Recent research has successfully demonstrated the production of functional carbonaceous materials from biomass using HTC [20]. In contrast to the dry biomass typically processed via pyrolysis, HTC enables the conversion of wet biomass into hydrochar [21]. HTC-derived hydrochar is rich in aromatic structures and oxygen-containing groups, which can be tailored further to create surface-functionalized materials [22,23].

Recent studies have shown that waste biomass such as rice husks, corn cobs, wheat straw, sugarcane bagasse, fruit peels, and coffee grounds can be transformed into highly porous activated carbons(AC) with CO_2 adsorption capacities reaching up to 7.0 mmol/g at 273 K [24]. However, further optimization of activation processes is needed to enhance surface area, porosity, and overall adsorption capacity to make these chars cost-effective and efficient adsorbents. The activation process plays a pivotal role in defining pore dimensions, which significantly influence adsorption performance [25].

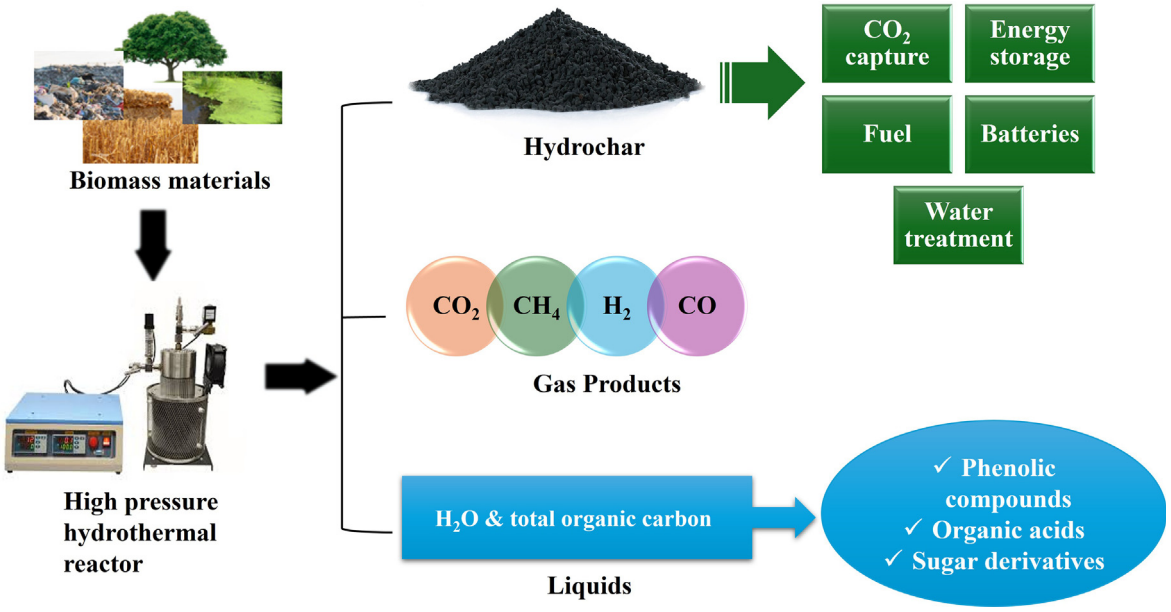

Fig. 2. The purpose and potential applications of biomass-derived product through HTC processing.

The most effective carbons for small gas molecule adsorption are those with a high volume of micropores or lower mesopores, targeting gases such as CO_2 (0.33 nm), CH_4 (0.38 nm), H_2 (0.29 nm), and N_2 (0.36 nm) [26]. Although the external surface of AC offers limited access to internal pore networks, the presence of surface oxides enhances their hydrophilic nature, which improves adsorption performance for both polar and non-polar molecules [27]. Typically, two primary processes are employed in the production of activated carbonaceous materials: two-stage physical (or thermal-gas) process and single-stage wet-chemical process [27]. Chemical activation, in particular, enhances surface properties and CO_2 adsorption by extending activation times and increasing functional temperatures, facilitating the release of volatile compounds and improving the porous structure of the char [28]. The activation method and the composition of char precursors determine the final surface functionalities and characteristics [29]. For example, incorporating basic nitrogen groups into carbon frameworks enhances the adsorption of acidic gases like CO_2. While traditional methods, such as post-synthetic amine modification or ammonia treatment, can suffer from stability issues and involve corrosive reagents, nitrogen-doped porous carbons can be synthesized directly from nitrogen-rich precursors.

Recent advances in microwave-assisted HTC have further revolutionized the field by providing an energy-efficient alternative to traditional HTC methods [30]. This approach has demonstrated significant potential in processing diverse biomass sources, including lignocellulose, algae, and cattle waste, with notable advantages such as shorter reaction times, higher yields, and reduced energy consumption [31]. Besides improving the structural properties of carbon materials, microwave-assisted HTC provides a scalable and sustainable method for developing advanced adsorbents with superior CO_2 capture capabilities.

To supplement these advancements, it is essential to comprehend the underlying mechanisms of HTC processes. HTC is a thermochemical process that pre-treats high-moisture biomass in water under pressure at elevated temperatures, operating in a closed reactor at 180–280 °C and 2–6 MPa pressure for durations ranging from 5 to 240 min [32]. This exothermic process reduces the oxygen and hydrogen content of biomass by removing carboxyl and hydroxyl groups through dehydration, decarboxylation, and decarbonylation reactions similar to the natural transformation of biomass into coal over millions of years. During HTC, the water in the feedstock generates autogenous pressure and the ionic product of water increases as the temperature approaches critical levels, resulting in a high concentration of H^+ and OH^- ions that catalyse acid- and base-catalysed reactions [33]. Additionally, the low dielectric constant of high-temperature water boosts the solubility of nonpolar feedstocks, leading to substantial cost reduction in production. HTC involves a series of complex thermochemical processes such as hydrolysis, dehydration, decarboxylation, and aromatization which convert biomass into carbon-rich compounds. The reaction conditions determine end products of HTC: under supercritical conditions, biomass macromolecules break down into their simplest forms and yield gaseous products, while under ambient conditions, they form a viscous bio-oil. Most biomass components, such as cellulose and lignin, are insoluble in ambient water but soluble in high-temperature or supercritical water [34]. Understanding these mechanisms is key for optimizing this biomass-conversion technology.

2.1. *Mechanisms involved in HTC*

2.1.1. *Hydrolysis*

Hydrolysis is the initial step of the reaction pathway, where ether and ester bonds of the biomacromolecules are cleaved via the addition of water. Each water molecule breaks a single linkage, converting polysaccharides such as cellulose, hemicellulose, starch, inulin, and xylan into sugars (e.g., glucose, fructose, xylose) and partially hydrolyzed oligomers. During the process, water provides hydroxide ions (OH^-) and, under hydrothermal conditions, protons (H^+), which facilitate the reaction. The breakdown of these monomers generates various organic acids such as acetic acid, lactic acid, levulinic acid, and formic acid. These acids contribute to the formation of hydronium ions (H_3O^+) in solution, which then act as catalysts for subsequent reactions [35]. The hydrolysis rate can also be further accelerated by the presence of acids or bases, which increase the reaction rate.

Acid-catalyzed hydrolysis breaks the β-1,4-glycosidic bonds in cellulose, yielding glucose or oligosaccharides [36]. However, this process is challenging due to the crystalline structure of cellulose, thus β-glycosidic bonds are more resistant to depolymerization compared to the α-bonds in amorphous starch. In contrast, hemicellulose, with its more amorphous structure, is more readily degraded at intermediate points, facilitating the breakdown of oligomers into simple sugars. This degradation process typically occurs at moderate temperatures of around 180 °C and with dilute acid concentrations, preventing further degradation of the resulting sugars. Hydrolysing hemicellulose yields a diverse array of sugars,

including the 6-carbon hexoses (glucose, galactose, and mannose) and the 5-carbon pentoses (xylose and arabinose). Additionally, acetyl groups and uronic acids may also form during hemicellulose hydrolysis [37]. Lignin is most effectively degraded hydrothermally at around 200 °C due to its high ether bond content. This produces low molecular weight reactive compounds through nucleophilic reactions. These compounds are essential for subsequent chemical transformations [38]. The detailed mechanism of the biomass conversion to hydrochar is shown in Fig. 3.

2.1.2. Dehydration

Following hydrolysis, dehydration involves the removal of hydroxyl groups, enhancing the hydrophobicity of the materials, and increases the carbon content of biomass by lowering the hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios [39]. Intramolecular dehydration facilitates the formation of carbon double bonds, which contribute to the development of aromatic rings in the char. Meanwhile, intermolecular dehydration may result in the formation of additional ether bonds, potentially increasing the reticulation and thermal stability of the biomass components [40]. For example, the dehydration and fragmentation of starch through ring-opening and C-C bond cleavage produces various soluble products including furfural-like compounds (5-hydroxymethylfurfural (HMF), furfural, 5-methylfurfural), acids, and aldehydes (acetaldehyde, acetonylacetone). Chheda et al. investigated the dehydration of fructose, glucose, and xylose to produce 5-hydroxymethylfurfural (HMF) and furfural using a biphasic reactor system [41]. By optimizing dimethyl sulfoxide (DMSO) and pH levels for each sugar, high selectivity is achieved (50–90 %) for HMF and furfural. Furthermore, hydrothermal conditions applied to biomass enhance physical dewatering through chemical changes such as lower water viscosity, colloidal structure disruption, and gas formation. Dewatering in HTC is an inherent part of the process. Physical dewatering typically precedes the dehydration step, as it reduces the overall moisture content of the biomass, making subsequent dehydration more efficient. This makes HTC an energy-efficient alternative to conventional drying methods, especially for wet feedstocks like sewage sludge and food waste. These effects have been utilized for drying lignite and peat, suggesting the potential for combined mechanical and thermal dewatering of lignite [19].

2.1.3. Decarboxylation

Decarboxylation reactions lead to the removal of carbonyl groups from the biomass matrix, significantly increasing the energy content of the biomass by reducing oxygen content. Carbonyl groups remain stable up to 150 °C, but decompose at higher temperatures potentially producing carbon dioxide and carbon monoxide [42]. Although the precise role of water in these reactions is not fully understood, potential sources of CO_2 during decarboxylation include condensation reactions, formic acid degradation, hydrothermal degradation of cellulose, and the cleavage of various chemical bonds. During HTC, decarboxylation occurs at a slower rate than dehydration [43].

2.1.4. Polymerization & aromatization

Glucose, fructose, and their decomposition products can undergo polymerization or condensation reactions, often driven by intermolecular dehydration or aldol condensation. These reactions result in the formation of soluble polymers, as organic molecules such as furfurals, furans, and aldehydes initially polymerize into aromatized compounds that subsequently condense into aromatic clusters [44]. The formation of hydrochar microspheres is likely governed by nucleation-growth, as described by the LaMer model [45]. Burst nucleation occurs when the concentration of aromatic clusters in the aqueous solution reaches the critical supersaturation threshold, triggering the formation of solid-phase micronuclei. These nuclei then diffuse toward the surface of the chemical species, expanding outward. Reactive oxygen functionalities (i.e., hydroxyl, carbonyl, and/or carboxylic groups), found on the particles surface facilitate binding to the microsphere surface. As a result of these interactions, stable oxygen groups such as ethers or quinones are generated. Consequently, the outer surface of the hydrochar particles has a high concentration of reactive oxygen groups while the core remains less reactive following the growth phase [35].

The hydrochar formation process can thus be summarized in stages: (i) hydrolysis; (ii) dehydration and fragmentation of soluble products; (iii) polymerization or condensation of soluble products; (iv) aromatization of the resulting polymers; (v) a brief burst of nucleation; and (vi) growth of the nuclei. All these stages are affected by the processing conditions. Hence, understanding the combined effects of feedstock, reaction temperature and time, catalyst, and pressure is crucial for optimizing the HTC process. Each of these parameters is explained in detail in

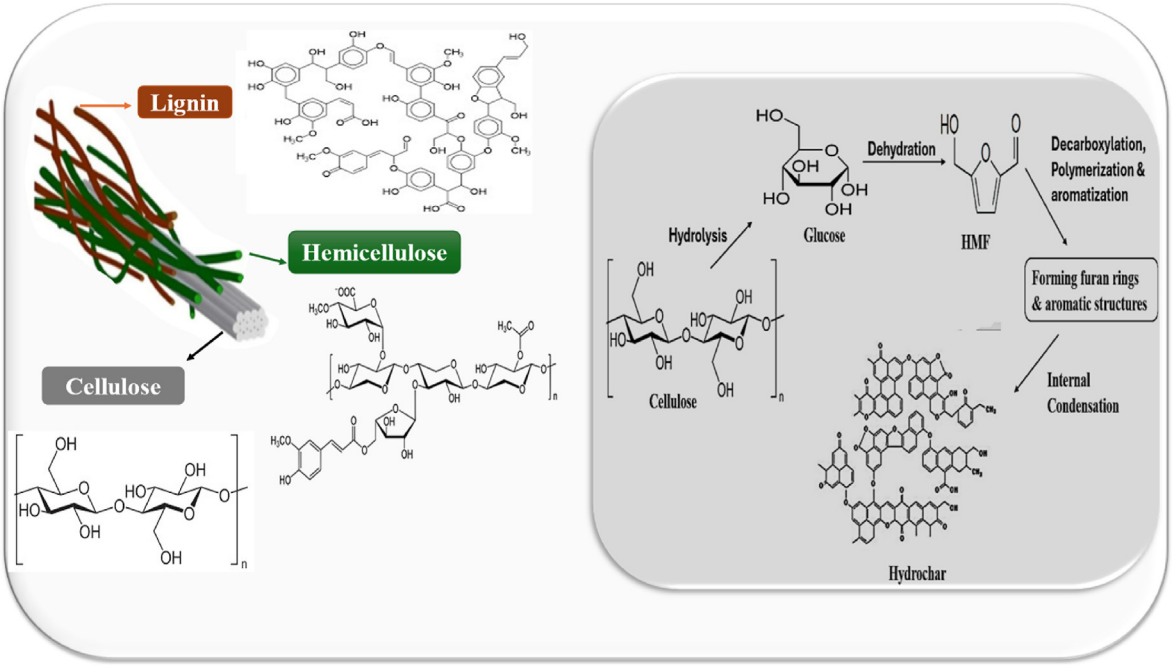

Fig. 3. Mechanism involved in hydrothermal carbonization of hydrochar.

the subsequent section.

2.2. Factors affecting HTC

2.2.1. Temperature

Temperature is a key factor in the HTC process, as it directly influences biomass breakdown and conversion efficiency. Elevated temperatures provide the necessary energy to disrupt biomass bonds, thereby increasing product yields. Additionally, temperature affects the nature of the product formed. For instance, lower temperatures lead to a higher yield of solid products; moderate temperatures promote liquid yields; and high temperatures promote gas production along with some liquid and solid byproducts [46]. Fig. 4(a) shows that from 220 °C to 300 °C, the char yield decreases with increasing reaction temperature, indicating enhanced carbonization at higher temperatures. Fig. 4(b) demonstrates that the moisture content of char is initially higher in biomass but drops substantially at elevated temperatures, improving the dewaterability. This improvement is attributed to structural changes and chemical dehydration, as the separation of hydroxyl groups alters the physical structure of the char. Furthermore, the average diameter and size distribution of carbonaceous particles are affected by reaction temperature (e.g., temperatures around 260 °C yield larger particles with a more homogeneous size distribution). Increased reaction temperature also enhances the proportion of carbon that transitions to the gas phase. In this context, Titirici et al. examined hydrothermal carbon spheres derived from lignocellulosic biomass, cellulose, and glucose [47]. Scanning electron microscopy (SEM) and dynamic light scattering (DLS) measurements revealed larger and more uniform glucose molecules and higher temperatures, with diameters increasing from 474 nm at 160 °C to 685 nm at 260 °C. Conversely, rye straw and cellulose only formed spherical particles at elevated temperatures and lost structural integrity at lower temperatures. The study demonstrates that cellulose undergoes structural disruption to generate spherical particles, whereas glucose products stem via nucleation and polymerization [47]. Pińkowska et al. investigated the impact of temperature on the hydrothermal decomposition of biomass, and found that when the xylan temperature increases, the pH decreases and reducing sugars are enhanced up to 220 °C. Beyond 220 °C, reducing sugars initially increased before declining slightly at 235 °C. Above 250 °C, gas production exceeds 50 % [48]. Since decarboxylation and volatilization are enhanced at higher temperatures, there is reduced retention of carbon in the liquid and solid phases. Variations in the decrease of carbon retention in solids likely arise due to differing study conditions [49].

2.2.2. Residence time

Residence time in the HTC process plays a key role in facilitating the polymerization of soluble monomers, which contributes to the formation of secondary hydrochar with a polyaromatic structure [51]. While temperature considerably influences the development of secondary hydrochar from non-dissolved monomers, residence time is particularly important for lignocellulosic materials. By controlling the residence time, HTC can induce pyrolysis-like processes. Longer residence times at elevated temperatures may simulate coalification effects, characterized by lower O/C and H/C ratios, although the mechanisms differ due to the formation of intermediate products [39]. As residence time increases during the hydrothermal process, nanoparticles grow progressively until they attain a final size, which is determined by the HTC processing temperature and residence time. At temperatures above 200 °C and with extended residence time, polyfuranic chains, which are prominent in HTC produced at 180 °C undergo further condensation, leading to the formation of more condensed sp^2-hybridized aromatic species via intramolecular condensation, dehydration, and decarboxylation reactions [47]. Ying Gao et al. studied the impact of residence time on HTC and found that extended residence times lead to a more complete decomposition of cellulose and hemicellulose, increasing the number of microspheres and altering their surface morphology [52].

2.2.3. Pressure

Pressure regulates the rates of hydrolysis and decomposition, which has a notable effect on biomass degradation. Maintaining pressure above a critical level makes biomass conversion more thermodynamically favorable, thereby increasing the efficiency of desirable product generation. Moreover, higher pressure positively impacts solvent density, further optimizing the process [53]. Typically, the reaction pressure is not externally controlled; instead, it is autogenic and corresponds to the saturation vapor pressure of water (subcritical water) at the reaction temperature. The pressure rises uniformly as the temperature rises or as more fluid is added [54]. According to Le Chatelier's principle, reaction pressure affects the reaction network by moving the equilibrium toward solid and liquid phases with fewer moles of reactants. While high pressure generally inhibits the dehydration and decarboxylation reactions, experimental evidence suggests that this effect is negligible in both hydrothermal carbonization and natural coalification. Increased reaction pressure also enhances the compaction and dissolution of encapsulated gases in water, facilitating the removal of extractables from biomass and improving access to the liquid phase [54]. Deepak et al. revealed that CO_2 uptake at 25 °C ranges from 2.46 to 3.05 mmol/g with an increase in pressure [24]. The research also indicated that increasing pressure enhances CO_2 adsorption capacity, with greater adsorption achieved at higher pressures, particularly in low-pressure environments. One possible explanation for this could be that high-pressure compression within the pore volume causes the molecules to be adsorbed on the sorbent surface throughout multiple molecular layers [55].

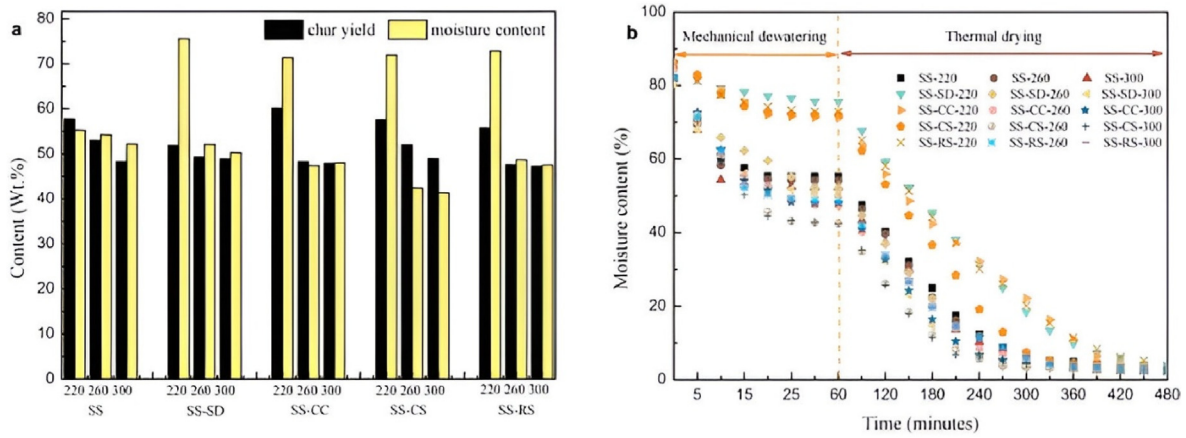

Fig. 4. (a) Effect of HTC temperature on char yields, and (b) dewatering performance [50].

2.2.4. Catalyst

Catalysts improve the performance of hydrochar by enhancing the degree of carbonization, surface modification, and incorporation of heteroatoms [56]. They also accelerate biomass decomposition by lowering activation energy, influencing the yield and quality of hydrochar [57]. The selection of an appropriate catalyst depends on factors such as high selectivity, cost-effectiveness, efficiency, and thermal stability [53]. Although some hydrolysis byproducts can act as autocatalysts, their impact is limited due to the decreased acidic dissociation constant at higher temperatures [58].

Acidic catalysts enhance reaction rates by increasing concentrations of H^+ and OH^- ions, which improves the breakdown of biomacromolecules and promotes hydrochar formation. The use of either acid or alkali catalysts can improve the quality of the final product by optimizing pore structure, adsorptive capacity, and surface area [59]. Conversely, the use of bases and/or salts during biomass liquefaction often inhibits char formation while enhancing the quality of oil products SEM images of hydrochars from non-catalytic runs (Fig. 5 a, c, e) show that heterogeneous surfaces form with cracks and cavities as temperature increases. This suggests the absence of secondary char formation, which typically requires more rigorous conditions. In contrast, catalytic runs (Fig. 5 b, d, f) resulted in carbon sphere formation due to the breakdown of C–C and C–O bonds in the biomass components, leading to secondary char formation. Lu et al. investigated the effects of various catalysts on the HTC of cellulose, including acetic acid, HCl, H_2SO_4, NaOH, $Ca(OH)_2$, NaCl, and $CaCl_2$. Acidic conditions enhanced cellulose dissolution, reducing solid yields at shorter residence times, while basic catalysts altered the pathways involved in 5-hydroxymethylfurfural (HMF) breakdown [60]. Similarly, Ameen et al. examined the influence of acidic catalysts on the HTC of Malaysian oil palm wastes (leaves, fronds, and shells) and reported that acidic catalysts increased the carbon content and yield of hydrochar while reducing oxygen and hydrogen levels through dehydration and decarboxylation processes, ultimately improving the carbon content of the hydrochar [61].

3. Lignocellulosic biomass for hydrothermal carbonization

Biomass encompasses all organic material derived from plants and animals including wood, agricultural residues, municipal solid waste, animal waste, by-products of food processing, and aquatic vegetation [39]. The utilization of biomass exhibits potential across diverse applications such as the production of transportation fuel, power, heat, and steam, as well as timber, animal feed, and food processing sectors [63]. On a global scale, biomass production on a dry basis reaches approximately 118 billion tons annually [64]. The elemental composition of biomass typically includes 47–53 % carbon (C), 5.7–6.5 % hydrogen (H), and 39–44 % oxygen (O), with sulfur (S) content below 0.1 % and nitrogen (N) ranging from 0.1 % to 0.5 % [65]. Structurally, biomass primarily comprises cellulose, hemicellulose, and lignin, along with smaller amounts of minerals and organic molecules like terpenes, tannins, waxes, fatty acids, and proteins. Cellulose, the most abundant polysaccharide in biomass, is composed of long, linear chains of glucose molecules connected by (1 → 4)-β-D-glycosidic ether bonds, with cellobiose as the repeating unit [66]. When treated with strong alkalis, such as 18 % NaOH, cellulose can be classified into three types: alpha-cellulose (insoluble), beta-cellulose (partially precipitated in neutral medium), and gamma-cellulose (soluble) [67]. Lignin, a complex three-dimensional amorphous polymer, consists of three primary phenylpropane units: p-hydroxyphenyl (H), guaiacyl (G), and syringyl (S). The proportions of these units vary by lignocellulosic species [68]. These units are linked by various ether and carbon-to-carbon bonds, such as β-O-4, 4-O-5, α-O-4, β–β, β-5, β-1, 5-5 [69,70] and contain additional oxygenated groups like alcohol, carbonyl, and carboxylic acids [71,72]. Hemicellulose, while also composed of sugar units like cellulose, differ in their structural characteristics. They are distinguished by the presence of side chains and a backbone typically made up of pentoses (e.g., xylans), mannans, or glucomannans, which alternate between mannose, glucose, or galactose units (galactans) [73]. SEM images of hydrochars derived from different biomass sources are shown in Fig. 6, illustrating the

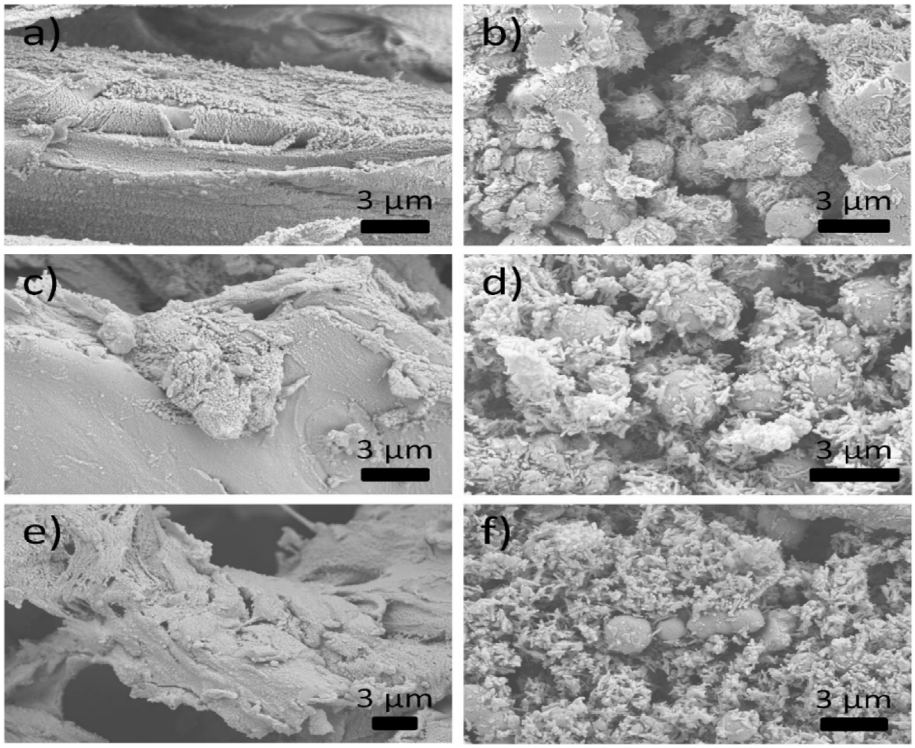

Fig. 5. SEM images of hydrochars obtained from the non-catalytic hydrothermal carbonization of Fir wood at (a) 225 °C, (c) 250 °C, (e) 275 °C and a residence time of 12 h and hydrochars obtained from the catalytic hydrothermal carbonization of Fir wood with $AlCl_3$-HCl catalyst at (b) 225 °C, (d) 250 °C, (f) 275 °C and a residence time of 12 h [62].

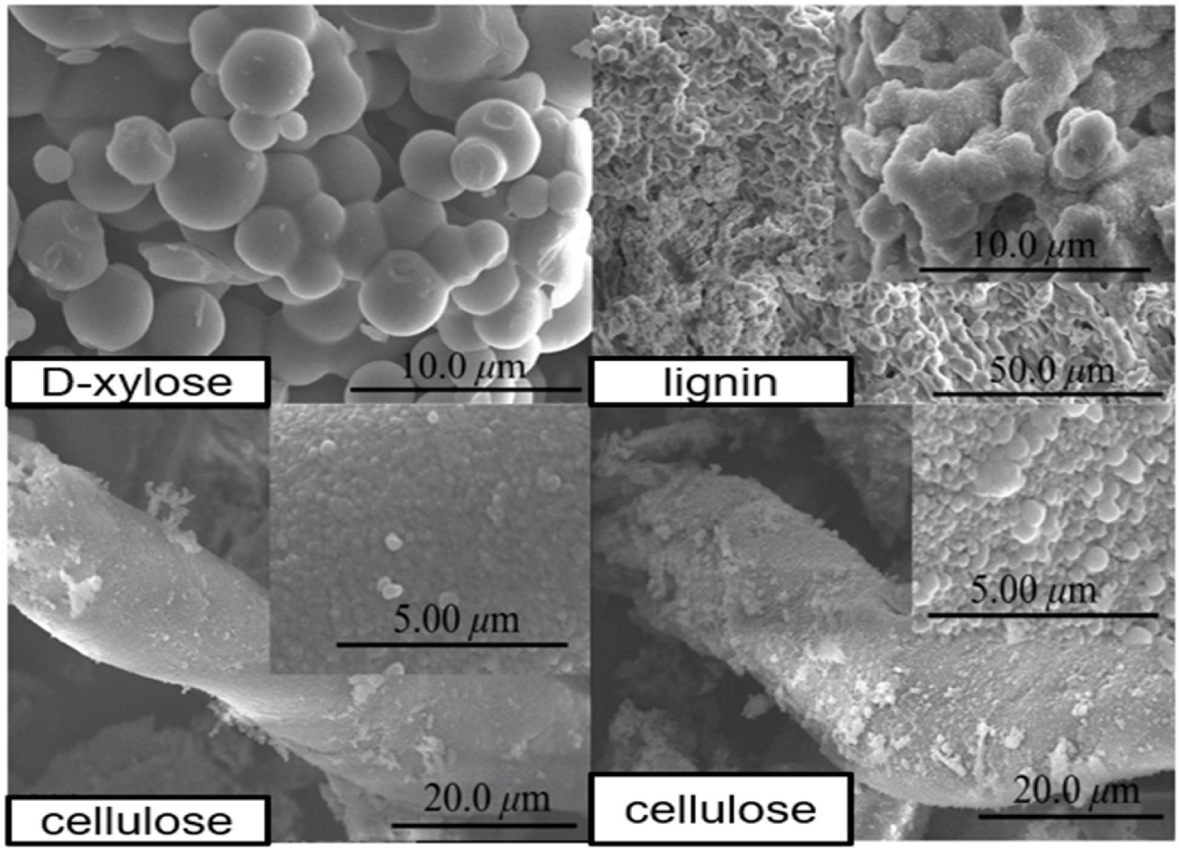

Fig. 6. SEM of d-xylose, lignin and cellulose derived hydrochars [74].

diverse microstructures of these materials.

The content of lignin, hemicellulose, and cellulose has a significant impact on the quantity and quality of hydrochar. Table 1 provides a comparative analysis of the chemical structure, thermal stability, hydrophobicity, solubility, biomass abundance, and applicability of these components toward HTC. Several factors determine the suitability of a biomass matrix for HTC including moisture and ash content, calorific value, fixed carbon, and the ratios of oxygen, hydrogen, nitrogen, and volatiles [75]. Every substance has these characteristics, and they vary depending on the growing environment [76], time [77], and age [78], among other factors.

Numerous studies have demonstrated that variations in feedstock types significantly affect hydrochar yields and characteristics [90,91]; however, only a limited range of feedstocks has been thoroughly examined through HTC. These include pure or model compounds (e.g., lignin, cellulose, xylose, glucose, and starch), mixtures of pure compounds, and more complex feedstocks (e.g., pinewood, paper, wood, and sweet corn) [90]. The following sections will provide a detailed description of how feedstock materials influence hydrochar production.

3.1. *Different feedstocks for hydrochar production*

3.1.1. *Forest residues*

Forest residues represent valuable sources of biomass [92] and include branches, leaves, and stumps left after thinning or timber harvesting, as well as wood manufacturing byproducts such as bark, sawdust, and trimmings. Wood is separated into gymnosperms (softwood) and angiosperms (hardwood) with a key distinction in their hemicellulose composition with regards to biomass output: softwoods primarily contain acetylated galactoglucomannans, while hardwoods are rich in xylans [93]. The composition of biomass, particularly the relative concentrations of cellulose, hemicellulose, and lignin, impacts its

Table 1
Comparative properties of cellulose, lignin, and hemicellulose.

Properties	Cellulose	Lignin	Hemicellulose	Reference
Chemical Formula	$(C_6H_{10}O_5)_x$	$[C_9H_{10}O_3(COH_3)_{0.9\text{-}1.7}]_n$	$(C_5H_8O_4)_m$	[53]
Structural Information	x = 500–10000; (1 → 4)-β-D glycosidic ether bridges linkages between glucose residues	Polymer of aromatic subunits in random structure; molecular weight: >10000 Da	Branched with variable monosaccharide residues; DP = 500–3000	[79]
Thermal Stability	Degradation>200 ^{0}C	200 ^{0}C	180 ^{0}C	[39]
Hydrophobicity	Hydrophilic	High	Partially hydrophobic	[80,81]
Solubility	Insoluble	Insoluble	Soluble >180 ^{0}C	[67,82,83]
% Present in Biomass	35–50 %	10–25 %	20–35 %	[64]
Applications	Textiles, Paper & Pulp, Biofuels, Food industry, Pharmaceuticals	Adhesives and Binders, Carbon Fibers, Dispersants, Biofuels	Biofuels, Food Industry, Biomedical Applications	[84–88]
Applicability towards HTC	Low	High	Intermediate	[89,89]

conversion efficiency. Generally, biomass with higher cellulose and hemicellulose content yields more oil, while higher lignin content produces more char due to the complex, more decay-resistant structure of lignin which accumulates during conversion [53]. Yu et al. demonstrated that sawdust hydrochar, with its high surface area, iodine value, and compression strength after pelletization and activation, can be effectively used as an adsorbent [94]. In addition, Zhong et al. investigated the influence of lignin content in different wood biomass types such as *Cunninghamia lanceolata*, *Fraxinus mandshurica*, *Pinus massoniana*, and *Populus tomentosa* at elevated temperatures between 280 and 360 °C and found that as lignin content increased, the yield of heavy oil decreased, while the production of residue increased [95]. This behavior is attributed to the repolymerization and cyclization of lignin fragments, which inhibited oil production [96]. The effect of hydrothermal processing on the physicochemical characteristics of wood vinegar which can be transformed into hydrochar was investigated by Xu et al., who found that cellulose and hemicellulose degraded completely at 230 °C and 280 °C, respectively [97]. They identified 230 °C as the optimal temperature for upgrading wood vinegar into hydrochar since higher temperatures lead to excessive degradation and reduced quality.

3.1.2. Agricultural residues

Agricultural residues, such as corn stover, rice husks, wheat straw, and sugarcane bagasse, are widely regarded as valuable lignocellulosic feedstocks for HTC due to their abundance and classification as waste materials. Guo et al. demonstrated the effectiveness of HTC on lawn grass at 200 °C and 240 °C for durations ranging from 30 to 180 min, yielding solid residues with mass yields between 31 % and 50 %. At higher temperatures and longer treatment times, the heating value of the hydrochar increased to 20.54 MJ/kg [98]. Analysis of the structure revealed that extended processing times encouraged the formation of more ordered hydrochar, with cellulose decomposition occurring at 240 °C, while amorphous components broke down at 200 °C. These findings underscore the importance of feedstock composition in hydrochar formation and its characteristics. Table 2 compares the hydrochar yields obtained from different feedstocks under varying HTC conditions, highlighting the impact of feedstock composition on hydrochar production. A key observation is the considerable variation in hydrochar yields among feedstocks, even within the same category (e.g., woody biomass). While longer residence times and higher temperatures generally enhance hydrochar yields, the optimal HTC conditions are highly dependent on the specific characteristics of each feedstock.

Table 2
The carbon yield from various biomass waste sources subjected to different HTC temperatures and residence times.

Biomass Waste	Temperature (°C)	Residence Time (hours)	Yield (wt %)	Reference
Wheat straw	200–260	6	9.9–54.5	[99]
Sugarcane bagasse	200–300	0.5	54.6	[100]
Corn stock	200	26	30–44	[101]
Rice husks	300	16	47.32	[102]
Wood meal	265	20	74.22	[74]
Cellulose	265	20	72.10	[74]
Lignin	265	20	68.43	[74]
d-Xylose	265	20	72.80	[74]
Pinewood	220	1	78.63	[103]
Poplar wood	220	1	79.81	[103]
Bamboo shoot shells	220	6–10	75.33	[104]
Soybean straw	220	4	54.7	[105]
Chlorella	220	4	26.7	[105]
Poplar wood chips	220	4	84	[106]
Loblolly pine	240	–	48.54	[107]
Municipal solid waste	230	0.5	97.67	[108]

3.1.3. Industrial waste

HTC is gaining traction as a promising method for managing industrial byproducts, particularly in addressing challenges related to dewatering and biological pollutants. For instance, urban municipal waste (UBM) such as paper sludge from wastewater treatment is often landfilled or incinerated, which is economically inefficient due to high dewatering and energy costs. This makes paper sludge management a significant operational and waste disposal challenge [109]. The composition of sludge in the pulp and paper industry differs between primary and secondary sources. Primary sludge is mainly composed of wood fibres, papermaking fillers, and lignin byproducts, while secondary sludge is largely microbial biomass mixed with non-biodegradable lignin [110]. Despite the challenges associated with paper sludge management, it can be repurposed into valuable materials such as adsorbents, bio composites, bioplastics, cement, and asphalt [111]. Hämäläinen conducted a study to understand the potential uses of paper and pulp industry sludges and found that the fuel properties of mixed sludges were greatly improved by HTC, which raised the higher heating value (HHV) from 14.9 MJ/kg to 20.5 MJ/kg [112]. HTC also resulted in increased carbon content, reduced oxygen content, and improved energy densification, although energy yields declined as hydrochar mass decreased due to decarboxylation. These improvements were seen regardless of the initial total solids content [113]. While hydrogen content in the paper sludge remained relatively unchanged, reactions such as demethylation and dehydration seemed less dependent on the elemental composition [114]. These findings suggest that HTC is a promising method for enhancing the fuel properties of industrial sludge, positioning it as a viable alternative for energy recovery and sustainable sludge management.

4. Non-lignocellulosic biomass waste for hydrothermal carbonization (NLBM)

Non-lignocellulosic biomass refers to a diverse category of organic waste materials that, unlike lignocellulosic feedstocks, contain minimal lignin and cellulose. Examples of NLBM include sewage sludge, cow manure, algae, animal hair, and bones, which are primarily composed of proteins, lipids, sugars, and inorganic compounds [115]. The complex and diverse composition of these materials presents significant challenges for both disposal and effective utilization. Conventional disposal techniques such as incineration, landfilling, and agricultural use can contribute to environmental pollution, particularly through landfill leachate and emissions [116]. To address these challenges, thermochemical processes for converting NLBM into bio-oil, with biochar and hydrochar as useful byproducts, have gained increasing attention in recent years. Unlike hydrochar, which is produced through HTC under water-saturated conditions, biochar is produced through pyrolysis in the absence of oxygen at elevated temperatures and is primarily used as a soil amendment [117]. Table 3 provides a summary of various studies on the HTC of different types of sludge, presenting the experimental conditions and resulting yields.

Urban municipal waste is another promising source of NLBM. As aforementioned the HTC process is particularly well-suited for treating UMW because it operates under wet conditions, eliminating the need for extensive drying, which is often a challenge with wet waste streams [135]. This makes UMW, including sewage sludge, an ideal candidate for HTC, as the process addresses both the moisture content challenges and the environmental burdens associated with non-lignocellulosic biomass (NLBM) management.

Sewage sludge, a major global byproduct of wastewater treatment, exemplifies the environmental and economic difficulties associated with NLBM [136]. It contains heavy metals, pathogens, and a variety of organic and inorganic substances that can be detrimental to the environment [137]. Different thermochemical methods, including gasification and pyrolysis, have been studied for their potential to extract energy from sewage sludge while attaining a notable reduction in volume. However, HTC stands out as a particularly promising approach avoiding

Table 3
Highlights significant variation in HTC yields influenced by sludge type, temperature, and reaction time.

Sludge	Temperature (°C)	Residence Time (hours)	Yield (wt%)	Reference
Sewage sludge	180–300	0.5	69–85	[118]
Organic sludge	180–240	1–4	51–61	[119]
Sewage sludge	150–250	0–2	65.67–80.31	[120]
Wastewater sludge	250	4	–	[121]
Municipal sludge	190–260	1–24	–	[122]
Faecal sludge	250	5	70–73	[123]
Digested sewage waste	200	4	60–68	[124]
Sewage sludge	250	5	41	[125]
Anaerobic sludge & alum sludge	230	4	76.96	[126]
Anaerobic sludge	200–300	0.5–2	72.9 ± 3.9	[127]
Wastewater sudge	170–260	1	31–89	[128]
Mixed centrifuged sewage sludge	200	1–8	48–55	[129]
Biological wastewater sludge	250	4	14–24	[130]
Processed faecal sludge	180–250	0.5–10	70–73	[131]
Sewage sludge	200	1–6	74–81	[132]
Fenton sludge & sewage sludge	320	1	98.55	[133]
Pulp and paper sludge	180–250	0.5–1.5	–	[134]

the high energy consumption associated with pre-drying [138]. HTC can transform the sludge into biofuels by operating at elevated pressures (5–40 MPa) and temperatures (200–600 °C) [51]. When compared to raw sewage sludge, HTC boosts the stability and sanitation of the hydrochar, reduces the volume of high-moisture sludge, and increases dewaterability. Hydrochar produced from HTC has a higher fixed carbon, higher ash content, and lower levels of volatile matter and leachable pollutants. Moreover, HTC increases the aromaticity, porosity, and polarity of hydrochar, making it more suitable for energy and material recovery [120,139,140]. Despite the rise in ash content with increasing temperatures, HTC markedly reduces the water-holding capacity of the resulting hydrochar, thereby streamlining subsequent handling and processing [127]. Chao et al. conducted a study exploring HTC of dewatered sewage sludge under sub- and near-critical conditions, and found that high temperatures and pressures reduced energy recovery but improved fuel quality, with optimal results at 320 °C [141]. This is likely due to the combination of increased energy input for processing and the potential loss of biomass that occurs at higher temperatures, which diminishes the quantity of energy that can be recovered from the final product. Additionally, the incorporation of calcium oxide (CaO) during HTC substantially increased hydrogen yield and promoted the fixation of inorganic elements and dehalogenation. High moisture content in the sludge, however, enhanced decarboxylation but reduced hydrogen and methane yields. Importantly, HTC was also shown to recover essential nutrients, especially phosphorus, while simultaneously degrading or passivating hazardous pollutants [142].

By transforming problematic NLBM wastes into valuable products, HTC thus represents an environmentally sustainable solution to waste management and resource recovery, addressing both economic and environmental challenges posed by these materials.

5. Functional design of biomass-based carbon materials for CO_2 capture

HTC is a growing area of study within research focused on hydrochar, particularly the influence of processing parameters on hydrochar properties and their environmental impact. Recent studies emphasize hydrochar systems for specific applications such as adsorbents for carbon sequestration, electrode materials for lithium-ion batteries and supercapacitors, catalysts for oxygen reduction reactions in fuel cells, and even host materials for hydrogen storage [143,144]. Hydrochar also holds promise in environmental remediation, where it can be used to adsorb and immobilize contaminants in soil and water systems. These versatile chemical reactions inherent to HTC processing present an opportunity to design carbon materials with a wide range of functionalities.

In hydrochar, key ratios such as H/C and O/C indicate aromaticity, oxygen content (related to thermochemical compatibility), and recalcitrant carbon content all of which directly affect its performance across various applications [145,146]. Despite these advantages, hydrochar often suffers from relatively low surface area and limited microporosity, which can reduce its efficiency in contaminant adsorption applications [147].

The surface functionalities of hydrochar play a pivotal role in enhancing its versatility and application potential. During HTC, polar oxygen-containing groups such as hydroxyl (-OH), carboxyl (-COOH), carbonyl (-C=O), and ether (-C-O) are introduced into hydrochar during the dehydration, decarboxylation, and polymerization processes [148,149]. These oxygen-containing functional groups on the surface of ACs induce a hydrophilic (polar) character, which complements the hydrophobic (non-polar) nature of the interior regions of hydrochar particles [150]. This dual nature of the surface promotes the adsorption of a wide range of chemicals, with surface oxidation generally limiting acidic adsorption while enhancing alkaline sorption [150]. These functionalities underscore the potential of hydrochar to be adapted for specific applications, ranging from environmental remediation to energy storage.

Additionally, optimizing the microporous structures of carbon-based materials is essential for enhancing CO_2 adsorption capacity and selectivity. The specific impact of biomass precursors and activation techniques on the specific surface area (SSA), total pore volume, and CO_2 adsorption capacity of porous carbons is shown in Table 4. Porous carbons are typically categorized into microporous (pore size $\leq$2 nm), mesoporous (2–50 nm), macroporous (>50 nm), and hierarchically porous structures, with various degrees of amorphous or graphitic morphologies and either ordered or disordered porosities [151]. Among these, small micropores (diameters less than 1 nm) are critical for CO_2 capture at atmospheric pressure, as they can accommodate large amounts of CO_2 through micropore filling mechanisms. The adsorption of CO_2 is influenced not only by the pore volume and BET surface area but also by the chemical interaction between the adsorbent and adsorbate. Additionally, doping carbonaceous structures with heteroatoms such as boron (B), nitrogen (N), sulfur (S), oxygen (O), and phosphorus (P) has been shown to enhance CO_2 adsorption capacity by increasing active sites within the carbon matrix [152,153]. This technique can lead to improved CO_2 capture performance, making it an important area of focus in the design of functional biomass-based carbon materials for environmental and industrial applications.

5.1. *Different functional group doping for hydrothermal carbonization*

5.1.1. *Nitrogen doped hydrochar*

Doping the carbon matrix with nitrogen functional groups enhances the interaction between carbon materials and acidic CO_2 molecules, providing additional active sites and improving adsorption efficiency [168]. Nitrogen functionalities, including pyridinic, amine/imine, pyrrolic, quaternary, and oxidized forms; are integrated into the carbon matrix during chemical activation and function as the adsorption site for CO_2 molecules, influencing both the surface area and microporosity of the adsorbent [169–172]. These nitrogen-based groups enable the diffusion of CO_2 molecules into small micropores by actively binding gas molecules [173]. Recent studies indicate that pyridinic and pyrrolic nitrogen strengthen hydrogen bonding between CO_2 molecules and C-H

Table 4
CO_2 adsorption performance and surface characteristics of AC materials derived from different biomass precursors under specific activation conditions.

Biomass precursor	Activation agent	Activation type	Activation temperature (°C)	SSA (m^2/g)	Total pore volume (cm3/g)	CO_2 adsorption (mmol/g)	Adsorption temperature (°C)	Reference
African palm shells	KOH	Chemical	600	365–1890	0.61	6.3	0	[154]
Ground coffee	CO_2	Physical			0.21	0.8 and 1.2	25 and 50	[155]
Sawdust	KOH	Physical	750	646–1195	0.0547–1.059	0.95	40	[156]
Chitosan	KOH	Chemical	700	1506	0.75	4.40	25	[152]
Macadamia nutshell	KOH	Chemical	700	1731	0.72	6.61	0	[157]
Sugarcane bagasse	KOH	Chemical	220	2080	1.316	1.99	50	[158]
Wheat flour	KOH	Chemical	700	648	0.299	5.70	0	[159]
Polysaccharides & Sawdust	KOH	Chemical	600	1700	0.79	4.8	25	[160]
Persian ironwood	H_3PO_4	Chemical	500	1954	1.63	6.78	30	[161]
Olive stones	H_3PO_4	Chemical	750	1178	0.45	10.9	30	[162]
Tobacco stem	KOH	Chemical	700	1922	0.788	8.0	0	[163]
Corn stover	KOH	Chemical	800	2442	1.55	7.14	0	[164]
Horse manure	CO_2	Physical	800	749	0.816	1.36	0	[165]
Grass cuttings	CO_2	Physical	800	841	0.379	1.45	0	[165]
Beer waste	CO_2	Physical	800	622	0.317	1.31	0	[165]
Bio sludge	CO_2	Physical	800	489	0.387	0.84	0	[165]
Beer waste	H_3PO_4	Chemical	600	1073	0.978	0.80	0	[165]
Banana-peel	KOH	Chemical	700	243.4	0.0931	3.8	25	[166]
Tobacco stem	KOH	Chemical	700	1922	0.922	8.0	0	[163]
Jujun grass and *Camellia japonica*	KOH	Chemical	800	3537	1.85	5.0 (0 bar) 21.1 (20 bar)	25	[167]

bonds, improving CO_2 adsorption. Pyridinic nitrogen donates one electron to the aromatic π-system, while pyrrolic nitrogen donates two p-electrons, contributing to the Lewis basic properties of the carbon material, which facilitates stronger hydrogen bonding with CO_2 molecules. In contrast, richness with other nitrogen-containing functional groups, like amine- or imine-N, pyrrolic-N, quaternary-N, and graphitic-N, can benefit from a stronger chemisorption effect for CO_2 adsorption [174]. Additionally, nitrogen doping increases the surface polarity of the carbon matrix, altering its electrical distribution and making it more suitable for CO_2 capture [175]. Adding nitridizing chemicals (such as urea, ethylenediamine, or melamine) is a novel way to increase the amount of these functional groups [176,177]. The selective removal of CO_2 from flue gases, which typically contain 85 % N_2 and 15 % CO_2, is particularly advantageous due to the larger quadrupole moment for CO_2 compared to nitrogen gas. The stronger binding affinity between CO_2 molecules and nitrogen-enriched carbons, as predicted by recent studies, allows for more efficient separation of CO_2 from nitrogen in gas streams [152,178]. Thus, the combination of micropore structures and nitrogen doping not only enhances adsorption capacity but also improves the selectivity of CO_2 over other gases, making these materials highly effective for carbon capture technologies.

5.1.2. Oxygen doped hydrochar

A valuable addition to the repertoire of rational hydrochar synthesis is oxygen-doped hydrochars. While surface oxygen groups are often understated in their role in CO_2 adsorption, recent research has begun to explore their potential, particularly in comparison to nitrogen-functionalized carbon materials [179]. Similar to nitrogen functional groups, the attached oxygen atoms can gain extra electrons from nearby carbon atoms, enabling them to act as Lewis bases by donating electrons to the electrophilic carbon atoms in CO_2 molecules, thereby enhancing chemisorption [180]. Additionally, these oxygen atoms can increase the polarity of the carbon framework, strengthening electrostatic interactions and promoting the initial adsorption of CO_2 molecules, particularly at low-pressure ranges. This increased polarity improves the affinity between the adsorbent surface and CO_2, facilitating enhanced capture efficiency [181].

Oxygen functional groups, predominantly located on the outer surface or edges of the basal plane of the carbon framework, are critical in enhancing CO_2 adsorption by providing high-affinity adsorption sites. These oxygen-containing functional groups, such as carboxyl (-COOH) and hydroxyl (-OH), create electrostatic conditions that improve the interaction between CO_2 molecules and the carbon surface [182]. The inclusion of oxygen atoms strengthens this interaction, as demonstrated by the -COOH group, where the carbon and hydrogen atoms display electropositivity, donating electrons to the negatively charged oxygen atoms. This electron distribution increases the adsorption capacity by enhancing the electrostatic attraction between CO_2 molecules and the carbon surface [163]. The presence of electronegative oxygen atoms, such as in hydroxyl and carboxyl groups, creates sites on the carbon surface that can efficiently capture CO_2 molecules. These interactions, driven by acid-base reactions and hydrogen bonding between the carbon surface and adsorbed CO_2, increase the overall adsorption capacity. With partial charges of −1.106 e and −1.124 e, oxygen atoms enclosed in carboxyl functional groups have the highest potential of any surface atom to donate electrons to surrounding adsorbate molecules [180]. These oxygen atoms act as Lewis bases, donating electron density to the positively charged carbon atoms in CO_2, which enhances CO_2 adsorption. Carboxylic groups thus increase the CO_2 adsorption capacity because acidic groups add a negative charge to the surface, which leads to higher electrostatic interactions, resulting in improved CO_2 adsorption [183]. Nitrogen molecules show a similar orientation behavior to CO_2 under these conditions. Khosrowshahi et al. investigated the role of different oxygen groups in CO_2 adsorption by calculating the binding energy (BE) between CO_2 molecules and edge-functionalized activated carbon using the DFT method [183]. The results showed that C=O and C–O groups had minimal impact on CO_2 adsorption, with BE values close to the pristine surface. In contrast, COOH and OH groups significantly enhanced CO_2 adsorption, with BE values of −14.06 kJ mol^{-1} and −9.06 kJ mol^{-1}, respectively. These groups interacted with CO_2 through hydrogen bonding, with distances of 2.078 Å (COOH) and 2.115 Å (OH), and electrostatic interactions between C(CO_2) and O(COOH) at 2.957 Å. Although both hydroxyl and carboxyl groups favored CO_2 adsorption, there was no direct linear relationship between the concentration of these groups and CO_2 uptake. However, the combined effect of both groups showed a strong correlation with CO_2 uptake ($R^2 = 0.90$), highlighting a synergistic effect between hydroxyl and carboxyl groups that significantly enhances CO_2 capture.

Peredo-Mancilla et al. demonstrated that AC carbon derived from corn stover and activated using H_3PO_4 exhibited CO_2 capture capacity, achieving 10.9 mmol/g [162]. In this case, the oxygen functional groups enhanced CO_2 affinity through electron donation. Similarly, Ma et al. achieved high adsorption capacities of 8.0 mmol/g at 0 °C and 4.8 mmol/g at 25 °C [163], and found that oxygen groups and pore structure

were responsible for the CO_2 capture in these materials (37 % and 63 % respectively). The presence of electronegative oxygen atoms and their interactions with CO_2 molecules improve not only adsorption efficiency but also selectivity, particularly in flue gas treatment and environmental applications.

5.1.3. Alkaline metals doped hydrochar

Introducing alkali metals to carbon surfaces markedly amplifies CO_2 adsorption by promoting electron transfer from basic metal oxides to acidic CO_2 molecules. Intrestingly, the addition of alkali metals has variable effects on the CO_2 adsorption. In this context , basicity is crucial because stronger basic sites can better interact with acidic CO_2 molecules, facilitating chemisorption [184]. Alkaline earth metals are commonly introduced onto the hydrochar surface as oxides (CaO, MgO) or hydroxides ($Ca(OH)_2$, $Mg(OH)_2$). Upon thermal activation, metal hydroxides decompose into oxides, enhancing the CO_2 adsorption capacity through the generation of reactive sites [185]. Functionalization with alkaline metals thus introduces new active sites that promote CO_2 chemisorption, improving uptake even when surface area decreases [186]. This is consistent with research that observed that a 34 % reduction in surface area led to a 3 % performance drop through metal oxide functionalization onto AC-CO_2 uptake rises as a result of the acid-base interaction between CO_2 and MgO [187].

Zhu et al. developed porous carbons via HTC followed by thermal activation with alkali metal oxalates, specifically $K_2C_2O_4$ instead of traditional activators like KOH or K_2CO_3[188]. The resulting $K_2C_2O_4$ activated microporous carbon exhibited a high specific surface area of 1076.3 m^2/g and a pore volume of 0.92 cm^3/g, which translated into exceptional CO_2 adsorption capacities of 5.32 mmol/g at 0 °C and 4.25 mmol/g at 25 °C under 1 bar pressure. The high CO_2 adsorption performance can be attributed to the generation of micropores during the activation, where the emission of volatile gases such as CO etches the carbon skeleton, creating both micropores and mesopores. This microporosity is crucial for CO_2 capture, particularly at lower pressures. Furthermore, the study revealed that activation at higher temperatures facilitated the development of more active sites, which not only enhanced pore formation but also contributed to the enlargement of existing pores, further improving adsorption efficiency. This material also demonstrated high CO_2/N_2 selectivity, stable cyclic performance with minimal adsorption loss, and rapid adsorption dynamics, highlighting its potential as a cost-effective sorbent for CO_2 capture and separation. The fewer activation reactions at lower temperatures result in fewer developed pores, while at higher temperatures, the increased reaction activity leads to the formation and expansion of micropores. This flexibility in tailoring pore structure combined with the ability of metal oxide to enhance basicity provides a powerful strategy for optimizing carbon-based sorbents for CO_2 capture.

For post-combustion carbon capture, the abundance of narrow micropores are more important than larger specific surface area (SSA) to achieve high adsorption capacity [189]. Despite their comparable kinetic diameters, the physicochemical characteristics of gases affect how well they are removed during adsorption; for example, carbon dioxide (0.330 nm) and nitrogen (0.364 nm) have different electronic characteristics [190]. Carbon dioxide, with its polar bonds and large quadrupole moment, interacts more strongly with adsorbent surfaces compared to nitrogen, which has a nonpolar triple bond. These electronic differences influence interactions (such as hydrogen bonding) thereby impacting the adsorption process, even if both gases have linear geometries. The key parameters that impact CO_2 capture include aromaticity, nitrogen functional groups, oxygen functional groups, and micropores. The primary indicator of the available sorption interphase on the hydrochar is the SSA, which is generally calculated using the Branueur-Emmet-Teller (BET) technique [191]. The mere increase in SSA is insufficient for enhancing adsorption as the development of nanoscale porosity, particularly micropores, plays a more decisive role [192]. In hydrochar materials, nanoscale porosity enhances mass transfer and active loading, improving catalytic and energetic performance. Direct carbonization often results in low SSA and underdeveloped microporosity, limiting adsorption capacity [150]. To overcome this limitation, post-treatment thermal activation under an inert atmosphere can create microporosity by removing organic molecules, thereby increasing the SSA to levels comparable to conventional AC [143]. Improving the micropore structure of solid adsorbents can improve their capacity, selectivity, and recyclability for CO_2. The adsorption mechanisms of hydrochar primarily include physical adsorption (physisorption) and chemical adsorption (chemisorption). Both mechanisms contribute to the overall effectiveness of CO_2 capture, depending on the surface chemistry and pore structure. Fig. 7 represents the various adsorption techniques on hydrochar for CO_2 capture.

5.2. Adsorption mechanism

5.2.1. Physical adsorption

Physisorption processes are primarily linked to van der Waals forces, which originate from polarization, dipole, quadrupole, and higher-pole interactions [193]. CO_2 capture on AC and char surfaces is primarily driven by weak van der Waals forces, facilitating physical adsorption without the need for activation energy [194]. Van der Waals forces are further classified as London dispersion forces, Keeson interactions, and Debye forces. The overall intermolecular force between the CO_2 molecule and the adsorbent is the sum of the electrostatic and van der Waals forces [195]. Physical adsorption is a temperature-dependent, reversible process, which exhibits enhanced adsorption at lower temperatures. Physisorption is the energetically favored CO_2 capture process for repeated use since it relies on weaker intermolecular interactions and can readily regenerate the sorbent [196]. Temperature, surface area, surface chemistry, and pore size distribution all affect the physical adsorption of CO_2 by hydrochar [197]. Micropores and mesopores enhance CO_2 capture by providing higher surface area and stronger van der Waals interactions, while oxygen-containing functional groups can improve adsorption through increased surface polarity. Additionally, lower temperatures favor CO_2 physisorption due to the exothermic nature of the process. Nitrogenous functional groups on char surfaces further enhance CO_2 adsorption by interacting with the acidic nature and quadrupole moment of CO_2 [152,198]. Quantities of the isosteric heat of adsorption, Q_{st}, can be used to experimentally observe the difference between physisorption and chemisorption. In general, Q_{st}, is high for chemisorption (40–800 kJ mol^{-1}), which is equivalent to the enthalpy of reaction, and low for physisorption (8–20 kJ mol^{-1}), which is equivalent to condensation heat of adsorbate [199]. In addition to direct surface interactions, the different gas components in a mixture may separate due to changes in their kinetic diameters or molecular weights, which cause varying rates of diffusion through the material. Although it is possible to use adsorption to selectively separate gas species other than CO_2 from a gas mixture, it is important to understand that CO_2 is typically more reactive than N_2, O_2, and methane because of its stronger quadrupole, which makes it an easier target for selective capture. High selectivity in the separation of CO_2 from N_2 is made possible by this parameter.

Shao et al. demonstrated the effectiveness of porous carbon derived from chitosan and KOH through a one-step chemical activation process. This material achieved a CO_2 capture capacity of 4.40 mmol/g at 25 °C and 1 bar, with a CO_2/N_2 selectivity of 21 [152]. The exceptional performance is attributed to the high nitrogen functionality, advanced textural features, and efficient dynamic adsorption capabilities, making it a promising CO_2 adsorbent. The study displayed that the CO_2 adsorption by chitosan corresponds to a physical adsorption process.

5.2.2. Chemical adsorption

Hydrochar is an effective adsorbent primarily through physical adsorption; however, advanced treatments such as activation and post-treatment can enhance chemisorption by strengthening electrostatic interactions, π-π interactions, and oxygen-rich functionalities. In contrast to

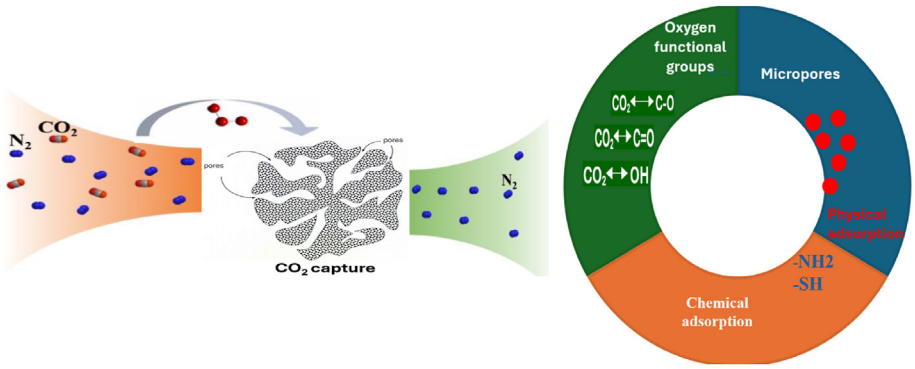

Fig. 7. Various adsorption techniques on surface of hydrochar.

physisorption, chemisorption involves the formation of covalent bonds between CO_2 and the adsorbent surface, which depends on the chemical characteristics of the material. Chemisorption of carbon materials is highly influenced by alkali ions and surface functional groups [200]. CO_2 adsorption in metal-organic frameworks (MOFs) proceeds through metal sites and surface functional groups, whereas chemisorption in char can be aided by functional groups containing nitrogen by forming zwitterions, carbamates, or bicarbonates. Similar to this, CO_2 chemisorption in biochar and hydrochar occurs when functional groups including those brought in by metal oxides are chemically altered through activation or naturally existing [201].

Selectivity and adsorption capacity can be improved by controlling the pore size distribution, as narrow pore diameters close to the kinetic diameter of CO_2 (0.33 nm) lead to stronger adsorption interactions. The high quadrupole moment of CO_2, coupled with its weak acidity, enhances adsorption compared to nonpolar gases like nitrogen and methane, which have larger kinetic diameters and lower adsorption energies [202]. Under pre-combustion circumstances, CO_2 adsorption takes place through a pore-filling mechanism in which larger pores gradually fill at higher pressures, reaching around 4 nm at 10 bar compared to less than 1 nm at atmospheric pressure. Both micropores and small mesopores contribute to CO_2 uptake at these pressures; multiple studies suggest that increased CO_2 adsorption capacities at high pressures are positively correlated with large specific surface areas and high pore volumes [151, 203]. In a recent study by Yuuki Mochizuki et al., porous carbon samples were prepared from various carbonaceous materials, including biomass and coal, to evaluate their CO_2 adsorption capabilities [204]. AC was synthesized by heat-treating the materials with melamine as a nitrogen source and K_2CO_3 as a chemical activator. Pore size properties were extensively analyzed, and their CO_2 adsorption performance was tested. The results indicated a notable correlation between specific surface area, micropore and CO_2 adsorption.

Tailoring hydrochar for pre- and/or post-combustion carbon capture offers the flexibility to meet various operational requirements. Further research on CO_2 adsorption in flue gas conditions is necessary to address the effects of thermal fluctuations and competing pollutants such as H_2O, N_2, O_2, SO_x, CO, and NO_x. These factors must be considered for practical applications in real-world environments.

6. Unlocking the potential of hydrothermal carbonization: evaluating CO_2 capture efficiency

HTC is an innovative and efficient way to produce sustainable energy and capture carbon dioxide, as it simultaneously converts wet biomass into hydrochar and captures greenhouse gases, addressing both waste management and greenhouse gas mitigation. Several recent studies have demonstrated HTC's feasibility as a CO_2 capture technology [205–207]. Adsorption pressure, surface species, specific surface area, pore volume, and pore size all have an impact on the CO_2 adsorption capacity of hydrochar. While some studies have explored physical activation methods, such as steam [208] and CO_2 [209], most have focused on chemical activation using various activation agents such as KOH [210–214], H_3PO_4 [215], $KHCO_3$ [216] and $ZnCl_2$ [215]. Among these, KOH activation has emerged as the most effective technique for enhancing CO_2 adsorption, likely due to the ability to generate new pores and increase the surface area and porosity of hydrochar. This process involves washing KOH-activated hydrochar with 0.1–0.15 M HCl to remove potassium, thereby creating a carbon matrix filled with K metal ions, which enhances porosity and surface area [209]. Studies indicate that materials subjected to KOH activation demonstrate the highest CO_2 sorption performance, with ultramicropore(<0.77 nm) density closely correlating with adsorption capacity. HTC combined with KOH activation has shown improvements in surface area and porosity, which directly boost CO_2 adsorption capabilities [217,218]. For instance, activating hydrochar with KOH at a 3:1 ratio and 700 °C resulted in a pore volume of 0.0931 cm^3/g and a surface area of 243.4 m^2/g. These enhancements lead to CO_2 adsorption capacities of up to 3.8 mmol/g at 1 bar and 25 °C, demonstrating the effectiveness for CO_2 capture [166]. Table 5 serves as a comprehensive reference for evaluating the performance of different hydrochars in CO_2 capture, highlighting the impact of feedstock type, activation conditions, and adsorption environment on their adsorption capacities and selectivity.

Zhu et al. synthesized porous carbon adsorbents using pineapple waste as a raw material for HTC, further enhancing porosity and CO_2 uptake by adding $Li_2C_2O_4$, $Na_2C_2O_4$, and $K_2C_2O_4$ to the hydrothermal carbonbamates [188]. The carbon activated with $K_2C_2O_4$ exhibited the highest CO_2 adsorption capacities of 5.32 mmol/g at 0 °C and 1 bar, due to the considerable volume of small micropores (approximately 0.92 cm^3/g). Rubiera conducted a comparative investigation between hydrothermal treatment followed by physical activation with CO_2 and in situ ionic activation to generate CO_2 adsorbents from high-moisture biomass waste [226]. Hydrothermal processing produced hydrochars that could be pelletized without binders and achieved a CO_2 adsorption capacity of 0.64 mmol/g at 15 kPa and 50 °C, outperforming some commercial AC. In contrast, the in situ ionic activation method yielded even higher CO_2 adsorption (0.78 mmol/g) with superior CO_2/N_2 selectivity and isosteric heat of adsorption, demonstrating the effectiveness of both techniques for creating high-performance CO_2 adsorbents. The primary concern with chemical activation is the potential for chemical corrosion. To mitigate this issue, various modification strategies, such as heteroatom doping, have been explored. One important factor for maximizing CO_2 adsorption in hydrochar is the formation of a well-developed microporous structure, as it influences adsorption capacity. Further research into optimizing this structure will enhance the effectiveness of HTC-derived materials for carbon capture applications.

In a study by Ma et al., tobacco stem and ethylenediamine were used to hydrothermally process carbon materials, resulting in oxygen and nitrogen doped porous carbons with surface areas ranging from 906 to 2940 m^2/g [227]. The experimental findings showed that AC derived from tobacco stem exhibited exceptional CO_2 adsorption capabilities at 1

Table 5
Various hydrochar feedstocks activated by different agents and conditions, focusing on CO_2 adsorption capacity and selectivity at specific temperatures.

Hydrochar Feedstock	Activation agent	Reaction Temperature (°C)	Residence Time (hours)	Adsorption temperature (°C)	CO_2 adsorption (mmol/g)	Selectivity (CO_2/N_2) at 1 bar	Reference
Corn stover	KOH	250	10	0	7.14	15.5	[164]
Pineapple waste	$K_2C_2O_4$	210	10	25	4.25	18.24	[188]
Pineapple waste	$K_2C_2O_4$	210	10	0	5.32	–	[188]
Rambutan peel	KOH	170	1.5	30	122.37	–	[147]
Camphor leaves & Camellia leaves	KOH	240	5	25	8.30	–	[219]
Pine sawdust	CO_2	220	4	25	2.89	–	[220]
Pine sawdust	CO_2	220	4	50	1.94	–	[220]
Pine sawdust	$KHCO_3$	220	4	25	3.30	–	[220]
Pine sawdust	$KHCO_3$	220	4	50	1.95	–	[220]
Algae	KOH	200	24	0	7.4	26.7	[221]
Sugarcane	N_2	180	24	25	2.8	58	[206]
Tobacco stalk	Urea	220	6	0	7.35	17	[176]
Tobacco stalk	Urea	220	6	25	4.83	17	[176]
D-glucose/Urea	KOH	180	12	25	4.26	21	[177]
D-glucose/Urea	KOH	180	12	0	6.70	21	[177]
Corn stalk	KOH	180	24	25	3.97	15:85	[222]
Empty fruit bunch of oil palm trees	KOH	250	–	25	3.71	11.2	[223]
Lignin waste	KOH	300–390	–	25	4.6	–	[224]
Lignin waste	KOH	300–390	–	0	7.4	–	[224]
Deoiled flaxseed	HCl	180–220	3–7	25	-	-	[225]

bar, with values of 4.33 mmol/g at 25 °C and 6.54 mmol/g at 0 °C. The enhanced electrostatic interactions between the carbon surface and CO_2 molecules, attributed to the nitrogen and oxygen doping, improved CO_2/N_2 selectivity. Further investigation by Sun et al. examined the effects of different additives (urea, sodium thiosulfate, thiourea) on preparing heteroatom-doped biochar via HTC, and found that nitrogen and sulfur competed for active sites during co-doping [153]. Although nitrogen and sulfur doping separately improved CO_2 adsorption by 11.9 % and 8.5 %, respectively, co-doping did not enhance performance due to mutual inhibition between functional groups. Notably, thiourea preserved amino groups and aided in pore formation.

Huang et al. studied a novel approach for fabricating porous carbon from microalgae for effective CO_2 capture and achieved the successful production of N, O dual-doped ultra-microporous carbon by using deep eutectic solvent-assisted hydrothermal carbonization (DES-HTC) and chemical activation [228]. The resultant material showed CO_2 adsorption capacity of 4.37 mmol/g and CO_2/N_2 selectivity of 32 at 25 °C and 1 bar. Characterization revealed high nitrogen (3.92 %) and oxygen (21.46 %) contents, alongside an ultra-micropore volume of 0.25 cm^3/g. The research findings indicate that DES-HTC has the potential to greatly improve CO_2 capture performance by accelerating the Maillard reaction, facilitating the integration of nitrogen and oxygen into the carbon matrix and enhancing the development of ultra micropores. The viability of high-performance CO_2 sorbents derived from algae was demonstrated by Sevilla et al. [221] as highly porous N-doped carbon materials were synthesized with surface areas of 1300–2400 $m^2\ g^{-1}$ and pore volumes up to 1.2 $cm^3\ g^{-1}$ from hydrothermal carbons derived from algae and glucose. These materials featured uniform micropores nominally smaller than 1 nm and exhibited CO_2 capture capacities of up to 7.4 mmol/g at 1 bar and 0 °C. However, despite the presence of various nitrogen functionalities pyridinic, pyridonic, and quaternary, their low basicity did not significantly enhance adsorption performance, emphasizing the importance of functional group selection in designing effective CO_2 adsorbents.

Greenhouse gas stabilization can be accomplished via bioenergy with carbon capture and storage (BECCS), which has the potential to produce negative net carbon emissions. Erlac et al. examined the efficiency of carbon capture and syngas production between raw wood gasification and biomass gasification followed by HTC [46]. Their findings indicate that while the HTC process limits carbon capture and introduces conversion losses, syngas production from bio coal is more efficient. The simulation findings demonstrate that, in comparison to the HTC-based method, which delivers slightly lower electrical efficiency (27.7 %) and capture rate (72.7 %), CCS-integrated gasification of raw wood achieves a higher electrical efficiency (28.6 %) and carbon capture rate (84.5 %). In conclusion, the molecular structure design through various approaches based on different mechanisms via HTC offer advancements in developing efficient carbon materials for CO_2 capture.

7. Upscaling of hydrothermal carbonization (HTC): cost-effectiveness and challenges

Although HTC technology has garnered significant attention from numerous researchers for producing hydrochar with various applications, the corresponding approaches are predominantly implemented in batch mode using lab-scale autoclaves, bench scales, and a few pilot scales. Recent studies on scaling up from laboratory to pilot scale have demonstrated that several critical process parameters must be considered when designing an industrial-scale HTC plant. These parameters include reaction temperature, pressure, residence time, type of feedstock, catalyst, biomass to water ratio and other relevant factors such as reactor type, energy recovery, mass balance, and energy balance. The type of feedstock, solids loading, reactor size, desired product quality, residence duration, and operating temperature all affect the mass balance and energy needs for the HTC process. The relationship between process parameters at the lab and pilot scales is useful for generating more favorable working conditions on an industrial scale. Shin et al. conducted a comparative study focusing on the production of a solid fuel equivalent to coal for power generation through HTC processes using waste wood [229]. Laboratory-scale HTC experiment showed that adding a catalyst reduced the mass yield but increased the calorific value. Pilot-scale tests confirmed that the optimal reaction temperature was 220 °C with a 1.5-h reaction time, and that increasing the catalyst concentration by 1.5 times yielded results similar to the laboratory scale, indicating the need for catalyst optimization in commercial plants. The optimized catalyst combination and concentration produced a solid fuel with an 18 % higher calorific value than coal, proving its potential as a biosolid fuel for power generation. Areeprasert et al. investigated alternative solid fuel production from paper sludge using hydrothermal treatment (HTT) in a lab-scale facility for pilot-scale implementation [230]. The paper sludge was treated under subcritical hydrothermal conditions, with temperatures of 180–240 °C in the lab-scale experiments and 197 °C as the optimum for the pilot plant, with a holding time of 30 min. The hydrothermally produced solid fuel showed improved higher heating value, carbonization evidenced by H/C and O/C atomic ratios similar to

coal, and a significant moisture reduction (19.5 %) compared to the raw paper sludges 4.1 %. The energy balance of the pilot plant indicated that the recovered energy exceeded the energy input, confirming the feasibility of using HTT to produce alternative solid fuel from paper sludge.

The optimal temperature and catalyst concentration, although showing a minor gap between the lab and pilot scales, remain largely consistent, suggesting that the fundamental reaction conditions are transferrable across scales. However, discrepancies in residence time and biomass-to-water ratio (BWR) could become more significant in upscaled systems. Further, upscaling becomes more complex when different feedstocks are combined. Regardless of whether it is paper sludge, agricultural waste, or other biomass types, every feedstock has unique properties, such as moisture content, chemical composition, and structural characteristics. In turn, this could influence hydrochar yield, quality (e.g., calorific value, carbon content), and the overall efficiency of the process. Thus, feedstock variability may dictate adjustments to temperatures, pressures, and catalyst concentrations for reliable products and sustained energy recovery on a wider scale.

Additionally, conducting a cost benefit analysis to determine the optimal process parameters is essential for effectively implementing the HTC process on a large scale. Overcoming technological, financial, and regulatory obstacles is thus necessary for the commercialization of hydrothermal carbonization. Models of industrial-scale HTC have been developed, and simulations have provided valuable insights into optimal conditions [231]. However, finding published data on energy consumption and yield for pilot or industrial-scale HTC plants remains challenging. HTC is recognized as an emerging waste-to-energy technology, specifically engineered for converting wet biomass feedstock without requiring energy input for drying, which is necessary in other methods. The global HTC market size is anticipated to grow significantly in the upcoming years.

After hydrothermal conversion, approximately 40–60 % of the carbon from the feedstock ends up in the byproduct aqueous phase (AP), also known as post-hydrothermal wastewater [232,233]. This leads to energy loss and requires additional investment for AP treatment. Techno-economic analysis indicates that wastewater treatment costs could constitute up to 90 % of the total cost of HTL waste disposal [234]. Therefore, improving AP disposal methods is crucial to enhance the feasibility of the hydrothermal process. After the separation of hydrochar, the aqueous phase typically retains water-soluble organic compounds such as acetic acid, formic acid, and furfural, along with phenolic compounds derived from lignin degradation.

Aqueous phase (AP) components including nitrogen and phosphorus, as well as organic carbon, can be useful nutrients for biological processes like algae cultivation and anaerobic digestion [235–237]. Nevertheless, the presence of hazardous substances such phenolic compounds and heterocyclic chemicals, which can suppress microbial activity and present environmental risks, frequently restricts the use of AP as a nutrient source [238]. During hydrothermal liquefaction (HTL) and HTC, the AP also accumulates substantial amounts of organic acids and other dissolved organics, including acetic acid, formic acid, and levulinic acid. In order to improve the process's overall energy recovery, these organics can either be immediately recovered through separation for possible use as platform chemicals or transformed into gaseous fuels like hydrogen (H_2) and methane (CH_4) through catalytic processes and hydrothermal gasification [239]. To optimize resource recovery and reduce environmental hazards related to the AP, appropriate treatment and valorization techniques are crucial. Effective utilization of all HTC products and by-products would minimize waste and production costs.

8. The future of hydrothermal carbonization

The research conducted into renewable HTC technology has the main incentive of advancing humankind into a more sustainable future, specifically when comparing to the current energy production and waste disposal methods. Technologies like hydrothermal carbonization that can capture and store CO_2 are increasingly important as the world seeks to mitigate climate change. HTC serves as an effective carbon sequestration method, helping to reduce greenhouse gas emissions and combat global warming. By optimizing HTC processes, hydrochar with high surface area and porosity essential for efficient CO_2 adsorption can be produced. The versatile surface functionalities and adsorption properties of hydrochar make it a promising material for environmental applications, particularly due to its ability to adsorb a wide range of contaminants and its renewable nature, positioning it as a key player in sustainable waste management and remediation strategies.

To further improve these qualities, future research will likely focus on enhancing these attributes through advanced activation techniques, such as employing alkali metals or environmentally friendly chemicals. Subsequent developments might concentrate on maximizing the stability and carbon content of hydrochar through HTC optimization, bolstering carbon storage. Long-term objectives include enhancing productivity and decreasing expenses. This entails developing reactors with higher energy efficiency and enhancing reaction conditions. Improvements in reactor design, particularly in heat and pressure management, may lead to reduced energy consumption and greater commercial viability of HTC for industrial CO_2 capture.

A techno-economic analysis on the integration of HTC of waste biomass with an algal bioreactor [240] revealed that HTC could reduce total operating costs by 17 % and carbon capture costs by 11 %, while providing nearly 50 % of essential inputs like carbon, phosphorus, nitrogen, and electricity. The integration was projected to improve the energy return on investment from 8.05 to 13.5. The HTC process is anticipated to generate 50,500 tons of solid fuel annually, with 26 % used for process heating and the remainder potentially sold, yielding an estimated value of $2.28 million if priced similarly to bituminous coal. The associated algae power plant is projected to cost $7.8 million, with annual operating costs of $1.9 million, while CO_2 recycling could save approximately $1.5 million per year. The potential economic benefits from valuable nitrogenous compounds in algae and offsetting food waste costs could further enhance viability, highlighting the need for further research into optimal feedstock, nutrient recycling, and economic modelling.

Future developments will focus on achieving scalability and commercial viability for HTC. This includes strengthening biomass feedstock supply chains, reducing costs, and improving process efficiency. In conclusion, HTC for biomass-based CO_2 capture holds a promising future, driven by potential efficiency gains, technological integration, the creation of advanced materials, policy and financial incentives. This technology has great potential to contribute to a low-carbon, sustainable future.

CRediT authorship contribution statement

Aleesha Nabhai: Writing – review & editing, Writing – original draft, Methodology, Investigation. **Nayomi Z. Plaza:** Writing – review & editing. **Nathan J. Bechle:** Writing – review & editing. **Said Abubakr:** Project administration. **Mert Atihan:** Technical support. **James Springstead:** Technical support. **Qingliu Wu:** Technical support. **Kecheng Li:** Project administration. **Jinghao Li:** Conceptualization, writing – review & editing, Supervision, Project administration.

Declaration of competing interest

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