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ADVANCES IN BIOMASS-DERIVED CARBON FOR INTEGRATED CARBON CAPTURE SYSTEMS

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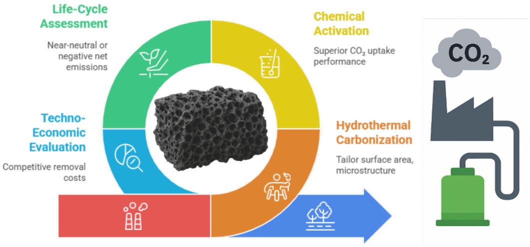
HIGHLIGHTS

- Chemical activation boosts CO_2 uptake to 2.86 mmol/g, outperforming physical routes
- HTC at 200°C to 260°C optimises pore structure and enhances carbon sorbent performance
- Integrated biomass carbons lower regeneration energy and outperform amine-based systems

GRAPHICAL ABSTRACT



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ABSTRACT

Biomass-derived carbon materials are gaining prominence as next-generation sorbents for low-carbon and economically viable CO_2 capture, owing to their tunable architectures, renewable origins, and strong life-cycle advantages. Much like transforming raw clay into a finely crafted ceramic through controlled firing, these materials evolve through carefully designed synthesis and activation routes that dictate their pore structure, surface chemistry, and ultimately their adsorption performance. This review consolidates recent advances in the mechanisms, synthesis pathways, activation methodologies, and sustainability considerations, shaping their development within integrated carbon capture systems. Hydrothermal carbonisation (HTC) in the 200°C to 260°C range plays a critical role in tailoring surface area and microstructure. The chemical activation consistently delivers superior performance, averaging CO_2 uptake values of 2.86 mmol/g, notably higher than 1.85 mmol/g obtained via physical activation. Life-cycle assessments highlight the potential for near-neutral or even negative net emissions, particularly when biomass residues are utilised as the energy source for activation. Techno-economic evaluations further reveal competitive removal costs that outperform those of conventional amine-based systems, driven by lower regeneration energy requirements and reduced capital costs. Collectively, this review uniquely integrates mechanistic understanding, activation-performance benchmarking, and sustainability evidence to establish clear design and deployment pathways for biomass-derived carbons in integrated carbon capture systems.

Introduction

Atmospheric CO_2 concentrations have continued to increase over the past few decades due to emissions from fossil fuel combustion, industrial activity, and land-use changes. This persistent accumulation of greenhouse gases drives global climate change and has intensified the demand for advanced carbon management solutions. This situation has elevated the importance of engineered carbon removal technologies, which combine capture functions with downstream utilisation, and has therefore made them strategically important (Carrascal-Hernández *et al.*, 2025). The progress of these technologies can be compared to a pressure relief system in an overfilled reservoir, where both slowing the inflow and actively drawing down the excess are required to restore balance. Solid sorbents represent a promising route toward efficient capture because they can deliver significant adsorption capacity while requiring lower regeneration energy than conventional solvent-based processes (Zentou *et al.*, 2025). Their development, however, is limited by challenges related to cost, material longevity, and environmental impact.

A broad range of sorbent classes has been explored for CO_2 capture, including metal-organic frameworks, zeolites, amine-functionalised solids, and conventional activated carbons. Each class offers distinct advantages but also suffers from inherent limitations. Metal-organic frameworks offer exceptionally high surface areas but often struggle with moisture sensitivity and high synthesis costs (Elhenawy *et al.*, 2020). Zeolites exhibit strong adsorption performance but can be less stable under variable humidity and elevated temperatures (Whaieb *et al.*, 2025). Amine-based solids exhibit strong chemisorption affinity but face issues with oxidative degradation and high regeneration energy requirements (Forse & Milner, 2021). Even conventional fossil-based activated carbons may require energy-intensive production routes with limited environmental benefits. These constraints create a clear need for sorbents that combine high performance with sustainable sourcing, chemical tunability, and robust operational stability.

Biomass-derived carbons present notable advantages due to their renewable origin, capacity to convert waste materials into functional products, and favourable physicochemical behaviour (Dan *et al.*, 2024). In contrast to fossil-derived carbons, biomass carbon materials can be produced from agricultural residues, forestry by-products, and other biowastes, aligning with circular economy principles. More importantly, such carbon materials can be tuned to have desirable pore structures, surface chemistries, and functional groups through controlled carbonisation and activation processes. The versatility of biomass-derived carbon, thus supports integrated systems that merge capture and utilisation, rather than treating them as distinct operations (Hanif *et al.*, 2023). From a sustainability perspective, biomass-derived carbons may offer lower regeneration energy, lower environmental impact, and enhanced life-cycle performance compared to conventional sorbents (Kundu *et al.*, 2024). Moreover, using biomass waste to produce carbon materials simultaneously supports waste valorisation and greenhouse gas mitigation. This strategic role positions biomass-derived carbon as a bridge between capture technologies and circular carbon utilisation.

Despite their potential, pristine biochars often exhibit limited surface area, a narrow pore-size distribution, and suboptimal CO_2-uptake kinetics, which limit their capture performance. This has driven research into engineered biomass carbons to enhance sorbent properties. Chemical and physical activation have been shown to increase microporosity and surface area, thereby boosting capacity significantly (Singh *et al.*, 2019). In addition, fine-tuning surface functional groups (e.g., oxygen, nitrogen) can improve CO_2 selectivity, binding strength, and regeneration behaviour. For instance, heteroatom doping has been shown to influence chemisorption pathways and improve uptake kinetics. Furthermore, there is growing interest in combining biomass-based sorbents with utilisation reactions, such as the catalytic conversion of captured CO_2, which require materials with not only adsorption capacity but also chemical reactivity (Creamer & Gao, 2016). Finally, from a deployment and commercialisation standpoint, engineered biomass carbons can be cost-competitive, especially when derived from low-cost agricultural residues and can support circular bioeconomy models (Nazir *et al.*, 2023). Their development could thus propel carbon capture technologies toward scalable, economically viable, and environmentally sustainable solutions.

This review evaluates biomass-derived carbon materials within the context of integrated carbon capture systems, defined here as frameworks in which carbon materials are developed and assessed alongside their synthesis routes, activation strategies, adsorption–desorption behaviour, and sustainability performance, rather than as isolated adsorbents. The analysis traces the progression of these materials from precursor selection through formation mechanisms, activation pathways, and ultimate performance in adsorption and conversion environments. Integration is conceptualised as the alignment of material design parameters with capture efficiency, regeneration energy, and system-level evaluation using life-cycle assessment and techno-economic analysis, rather than solely physical plant integration. The discussion combines fundamental adsorption principles with synthesis routes such as hydrothermal carbonisation (HTC) and pyrolysis, and examines how activation strategies affect pore development, surface chemistry, and carbon dioxide uptake. Economic and environmental implications are also addressed, with life-cycle assessment and techno-economic analysis clarifying the advantages and limitations influencing large-scale deployment. By synthesising insights from materials science, process engineering, and sustainability evaluation, this review establishes a unified framework for assessing the practical viability of biomass-derived carbons within integrated carbon capture platforms and highlights unresolved challenges and emerging opportunities to inform future research and industrial implementation.

Although several review articles have addressed biomass-derived carbon materials for CO_2 capture, most existing studies remain fragmented in scope and focus on isolated aspects of material performance. For example, many prior reviews emphasise adsorption mechanisms or synthesis routes without systematically linking activation strategies to quantitative benchmarks for CO_2 uptake, regeneration behaviour, and sustainability outcomes. Other studies provide broad overviews of activated carbons but lack explicit techno-economic or life-cycle perspectives, limiting their relevance for large-scale deployment. Furthermore, policy and practical implications are rarely discussed and data-driven visualisation of performance trade-offs across activation routes is often absent. In contrast, the present review explicitly bridges these gaps by integrating mechanistic understanding, synthesis and activation pathways, performance benchmarking, and life-cycle and techno-economic evaluation within a unified framework. Table 1 presents a comparative analysis of representative review articles, clearly highlighting how this work advances beyond the existing literature in scope, depth, and system-level relevance.

Table 1: Comparison of the present review with previous studies on biomass-derived carbon material on carbon capture technology, highlighting differences in scope, methodology, and contributions

Fundamental Mechanism	**Synthesis Strategies**	**Activation Pathway**	**Economic and Environmental Implications**	**Policy and Practical Implications**	**Data Visualisation**	**References**
✓	✓	✓	✗	✗	✗	Mohd Azmi *et al.* (2022)
✓	✗	✓	✗	✗	✗	Singh *et al.* (2019)
✓	✗	✗	✗	✗	✗	Goel *et al.* (2021)
✗	✗	✓	✗	✗	✗	Dissanayake *et al.* (2020)
✓	✓	✓	✓	✗	✗	Umar *et al.* (2025)
✓	✓	✓	✓	✓	✓	This article

Note: ✗: Not-included; ✓: Included.

Fundamental Mechanisms of Biomass-Derived Carbon for Carbon Dioxide Capture

Biomass-derived carbons typically capture CO_2 through a combination of physical and chemical adsorption. Physical adsorption is governed by weak van der Waals forces and is strongly influenced by the textural properties of the carbon structure, particularly the distribution of pore sizes and the available surface area. The effectiveness of physical adsorption is fundamentally linked to molecular sieving, in which only gas molecules with kinetic diameters smaller than the accessible pore openings can diffuse into the porous network of activated carbon (Demiral & Demiral, 2018). Once inside the pore system, CO_2 can form multilayer arrangements driven by weak intermolecular forces, facilitating rapid uptake and release. This mode of adsorption is dominant in unmodified activated porous carbon and is characterised by an isosteric heat of adsorption typically below 30 to 40 kJ/mol (Patel *et al.*, 2024). Ultra-micropores provide the most substantial confinement effects for CO_2, which explains why pore size often exerts a greater influence on adsorption capacity than surface area or pore volume (Yurduşen *et al.*, 2020).

In addition to physical adsorption, chemical adsorption arises from specific interactions between CO_2 and surface functional groups on the carbon matrix. These interactions typically involve basic sites, such as nitrogen or metal-enriched regions, that can form stronger, often localised chemical bonds with CO_2. Chemical adsorption involves the formation of covalent-interactions between reactive sites and CO_2, resulting in monolayer adsorption with significantly higher isosteric heats of adsorption. At elevated temperatures, the relative importance of chemical adsorption increases because surface chemistry becomes the governing factor for adsorption behaviour (Patel *et al.*, 2024). Functional groups including oxygenated and nitrogen-containing moieties, control these interactions and determine whether the carbon surface behaves as an acidic or basic adsorbent (Montes-Morán *et al.*, 2004). In addition, chemisorption can occur through reactions with inorganic mineral residues within the carbon structure, forming metal carbonates. Metals such as calcium, magnesium, iron, and aluminium are often introduced to promote this pathway (Leventaki *et al.*, 2024).

Among the various nitrogen functionalities introduced into carbon frameworks, pyridinic nitrogen has been widely identified as a key contributor to enhanced CO_2 adsorption selectivity at low pressures (Shibuya *et al.*, 2022). Pyridinic-N, situated at the edge of graphene-like carbon domains, introduces a lone pair of electrons that creates strong Lewis basic sites, which preferentially interact with CO_2's quadrupole moment and increase the local electron density to favour chemisorption over physisorption (Guo *et al.*, 2016). The acid-based interaction increases adsorption affinity without excessively raising regeneration energy, making pyridinic-N particularly favourable for low-pressure and dilute CO_2 capture scenarios. In contrast, pyrrolic-N contributes less to CO_2 binding due to electron delocalisation within the five-membered ring, while graphitic (quaternary) nitrogen primarily enhances electrical conductivity and structural stability but plays a secondary role in CO_2 selectivity (Sharma *et al.*, 2015). It has been reported that higher isosteric heats of adsorption and improved selectivity for carbons enriched in pyridinic-N, confirming its dominant role in low-pressure CO_2 capture (Shi *et al.*, 2023).

The integration of such functionalities enables biomass-derived carbons to operate efficiently across a range of pressures and gas compositions. Chemical adsorption enhances selectivity and performance at lower CO_2 partial pressures, whereas physical adsorption supports fast sorption kinetics and lower regeneration energy requirements. This interplay creates a dual-mode system that can be tuned through activation strategies, precursor selection, or targeted surface modification to meet the requirements of specific capture scenarios. Such tunability provides a flexible pathway for optimising carbon materials for applications involving dilute gas streams or dynamic operating environments.

Synthesis Strategies of Biomass-Derived Carbon for Carbon Dioxide Capture

HTC is an environmentally friendly method for converting biomass into value-added products, including hydrochar (a carbon-rich solid), a liquid phase (containing dissolved organic compounds), and gaseous by-products. This process mimics natural coalification, which forms fossil fuels with high carbon content. Compared to pyrolysis, HTC offers distinct advantages such as lower emissions and the ability to efficiently process biomass with high moisture content without requiring extensive drying. This not only reduces energy consumption but also enhances the overall cost-effectiveness and sustainability of the process, making HTC a superior alternative to conventional thermal conversion methods (Antero *et al.*, 2020). HTC operates at relatively low temperatures under autogenous pressure, utilising water as both a solvent and reaction medium. In subcritical conditions (below 374°C), water undergoes significant changes, reducing its dielectric constant and strengthening its ionisation, leading to the formation of hydronium (H_3O^+) and hydroxide (OH^-) ions (Wang *et al.*, 2018). This enhanced reactivity allows acid-catalysed reactions to proceed without the need for external acid addition. The unique thermochemical properties of subcritical water facilitate hydrolysis, dehydration, and aromatisation reactions, promoting carbonisation. It should be noted that HTC can generate process wastewater rich in dissolved organic and inorganic species, necessitating appropriate treatment or valorisation strategies to fully realise its environmental benefits at scale.

Pyrolysis remains the principal route for producing biochar and activated carbon because it offers a controllable, scalable approach to transforming biomass into carbon-rich solids. When biomass is heated in an inert atmosphere, it undergoes thermal decomposition in a manner similar to a slow distillation process in which lighter components are driven off and heavier carbon frameworks are progressively consolidated. Volatile compounds are released, while aromatisation and carbonisation reactions reorganise the structure into a more thermally stable matrix (Quan *et al.*, 2023). Optimised conditions can yield biochars with high fixed carbon content and a well-developed aromatic backbone. Compared to HTC, pyrolysis allows greater structural aromatisation and thermal stability, making pyrolytic biochar a more robust precursor for subsequent physical or chemical activation. Pyrolysis temperature strongly governs fixed carbon content, pore evolution, and surface chemistry, with higher temperatures promoting aromatic ring condensation and enhanced microporosity, albeit at the expense of solid yield (I *et al.*, 2024) the produced biochars were designated as BCG-300, BCG-400, BCG-500, and BCG-600, respectively. The produced biochar's were characterised by different analytical techniques. These include the proximate and elemental analyses, morphological, crystallographic, functional groups, and specific surface area analyses were investigated using elemental analyser, scanning electron microscopy (SEM). Table 2 provides a direct comparison between HTC and pyrolysis, highlighting their respective operating conditions, structural outcomes, energy demands, and implications for producing biomass-derived carbon materials suitable for CO_2 capture.

Table 2: Comparison between HTC and pyrolysis for the production of biomass-derived carbon materials for CO_2 capture

Aspect	HTC	Pyrolysis
Reaction medium	Subcritical water (autogenous pressure)	Inert atmosphere (N_2, Ar)
Feedstock moisture tolerance	High (wet biomass directly processed)	Low (drying usually required)
Main solid product	Hydrochar	Biochar / activated carbon precursor
Dominant reactions	Hydrolysis, dehydration, decarboxylation	Devolatilisation, aromatisation, carbonisation
Initial surface area	Generally low to moderate	Moderate to high
Structural features	Oxygen-rich, spherical particles are common	Aromatic, thermally stable carbon matrix
Energy demand	Lower	Higher
Suitability for CO_2 capture	Indirect (via post-activation)	Direct and indirect (via activation)
Sustainability advantages	Low energy input, wet biomass utilisation	Mature technology, scalable infrastructure

The evolution of hydrochar structure during hydrothermal carbonisation resembles the controlled transformation of clay in a kiln, where temperature and time determine whether the material becomes porous and delicate or dense and compact. Reaction temperature is the primary driver of pore development, as the progressive breakdown of hemicellulose and cellulose releases volatiles that carve out internal voids and expand the nascent carbon matrix. As the temperature rises, this devolatilisation process promotes the formation of reactive intermediates, thereby increasing surface area and pore volume. When temperatures become excessive, however, the system shifts toward aromatisation and cross-linking reactions, which contract the microstructure, reducing accessible porosity and limiting surface area (Chaves Fernandes *et al.*, 2020). Residence time acts as the second sculpting parameter in this thermochemical process. Extended residence periods, in contrast, encourage the repolymerisation of condensed fragments, which can obstruct emerging pore channels and reverse earlier gains in porosity (Cao *et al.*, 2021). This balance is particularly evident in lignocellulosic feedstocks, where high-temperature exposure promotes the formation of spherical carbonaceous aggregates from polymerised sugar monomers, altering surface texture and pore connectivity.

Figure 1 illustrates the combined influence of temperature and residence time during hydrothermal carbonisation on the structural characteristics of hydrochar, including specific surface area, pore size, and pore volume. The results indicate that an optimal window of thermal and temporal conditions enhances pore development while preventing excessive structural densification that would otherwise diminish overall porosity. As temperature increases, the thermal decomposition of hemicellulose and cellulose enhances porosity, primarily through the release of volatile organic compounds and the formation of intermediate species (Tasca *et al.*, 2019). However, at excessively high temperatures, secondary reactions such as aromatisation and polymerisation contribute to structural densification, ultimately reducing surface area and pore volume. Similarly, prolonged residence time facilitates the volatilisation of organic components, leading to increased pore formation and higher BET surface area. However, excessive residence time may trigger repolymerisation reactions, leading to pore blockage and a decline in porosity (Djandja *et al.*, 2023). Furthermore, lignocellulosic biomass exposed to high temperatures promotes the formation of carbonaceous spheres via the polymerisation of sugar monomers, further modifying the surface morphology (Cavali *et al.*, 2023).

Heating rate governs thermochemical transformation in much the same way that the timing of a kiln firing shapes the integrity of ceramic material. It controls how quickly biomass crosses the threshold from biopolymer structure to consolidated carbon, and it determines whether stresses accumulate gradually or erupt abruptly (Haykiri-Acma & Yaman, 2009). A fast-heating regime accelerates devolatilisation but can create steep internal temperature gradients that disrupt early pore formation, while slower heating encourages a steadier collapse and reorganisation of cell wall components. Studies show that intermediate heating rates sometimes reduce surface area because volatile species escape too rapidly to form coherent pore channels, whereas at sufficiently high rates the decomposition front becomes more uniform, supporting improved pore development and microstructural consolidation (Muzyka *et al.*, 2023; Santos *et al.*, 2023). Comparable thermochemical behaviour is observed in hydrothermal carbonisation, where elevated temperatures intensify dehydration and decarboxylation reactions, enhancing carbon recovery and thermal stability while reducing hydrochar yield as water-mediated decomposition accelerates. At higher HTC temperatures, the formation of acidic oxygenated groups leads to a measurable decline in hydrochar pH, reflecting the chemical signatures of increasingly advanced hydrothermal degradation (Zhang *et al.*, 2022).

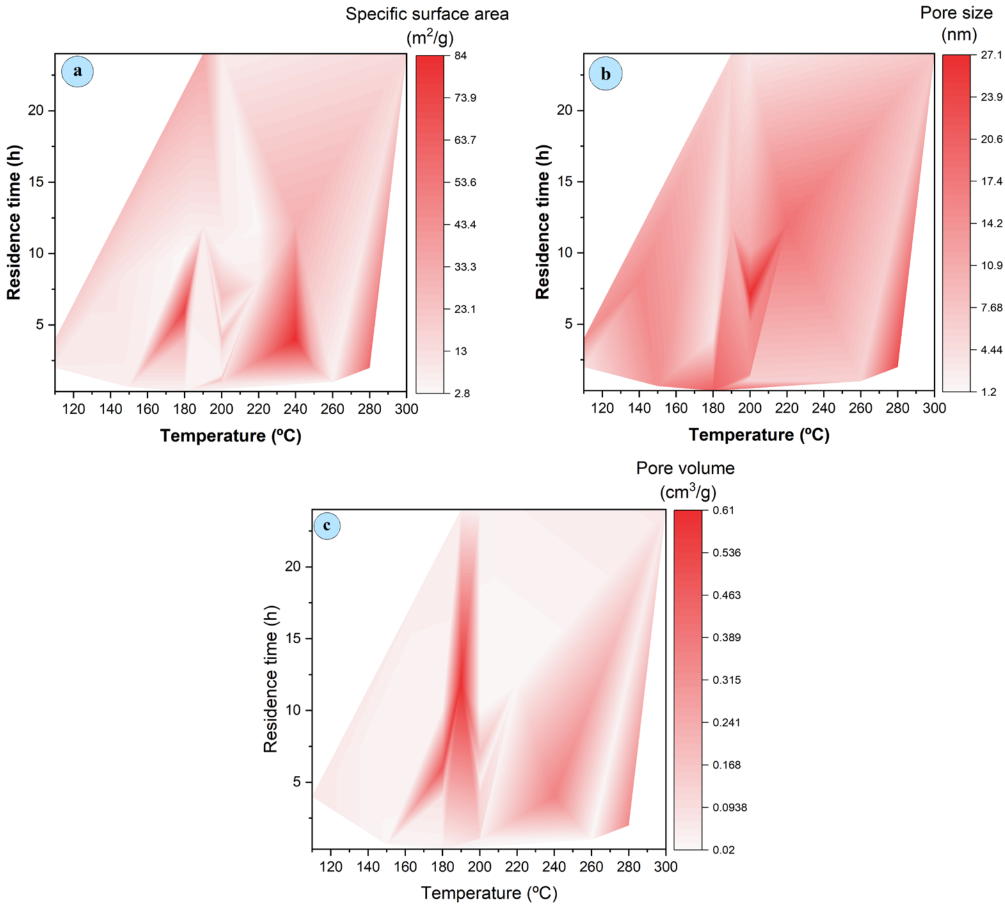

Figure 1: Influence of temperature and residence time on (a) specific surface area, (b) pore size, and (c) pore volume of the obtained hydrochar from HTC

Note: The plotted curves represent schematic trend profiles synthesised from reported experimental data in the literature.

Source: Ighalo *et al.* (2022); Shafizadeh *et al.* (2023)

Activation Domain of Biomass-Derived Carbon for Carbon Dioxide Capture

Activation of biomass-derived carbon can be understood as a form of architectural renovation in which a rigid and compact structure is transformed into a building filled with corridors and chambers that invite selective guest molecules such as CO_2. Once biochar is formed through carbonisation, activation reshapes its internal framework by generating pores, cracks, and chemically active sites that enhance adsorption performance. This transformation is achieved through physical or chemical pathways. Physical activation employs steam or CO_2 to remove volatile residues and open the carbon matrix, while chemical activation introduces agents such as KOH or $ZnCl_2$ that react with the char and reorganise its internal structure (Singh *et al.*, 2019). Pretreatment involves treating the raw biomass with acids or metal salts to influence the carbon matrix during pyrolysis, while post-treatment adjusts the already carbonised material using gases, salts, acids, bases, or metal species (Kumar *et al.*, 2020).

Physical activation operates much like sculpting a dense block of material into a finely carved structure, in which controlled removal rather than addition creates the functional architecture. In this method, carbonisation produces a rigid carbon matrix, which is subsequently opened by reactions with hot gases such as steam or CO_2. At elevated temperatures, these gases selectively erode disordered carbon domains, revealing a connected pore network that governs the adsorption performance of the final material (Singh *et al.*, 2019). Steam provides rapid, aggressive pore development because its small molecular size enables deep penetration into the carbon matrix (Figure 2), whereas CO_2 reacts more slowly and therefore introduces uniform microporosity. Experimental evidence demonstrates that steam activation often yields higher surface area but lower overall product yield due to structural degradation, whereas CO_2 activation offers a more conservative etching process that preserves carbon mass while enhancing pore uniformity (Linares-Solano *et al.*, 2000; Yang *et al.*, 2010). Although physical activation is simple and economically attractive, it requires precise control of temperature, residence time, and gas composition to prevent tar deposition, pore collapse, or excessive burn-off that reduces carbon recovery. This method represents a balance between structural refinement and material preservation, where subtle adjustments in operating conditions determine the quality of the activated carbon produced for carbon capture.

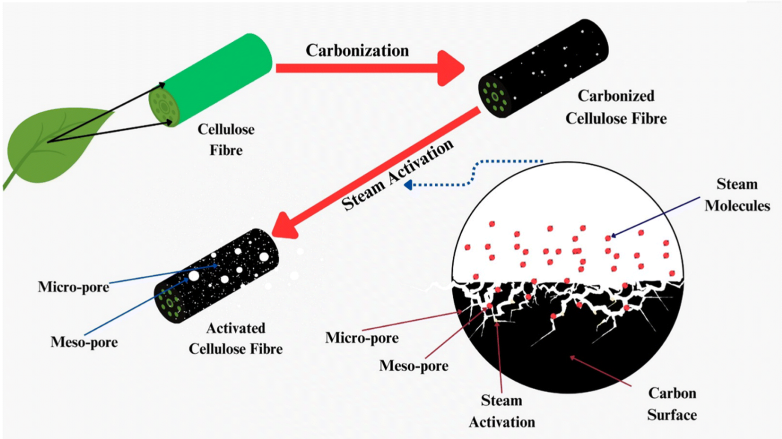

Figure 2: Schematic representation of steam-induced activation of carbon surfaces

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Source: Reprinted with permission from Kundu *et al.* (2024)

Chemical activation behaves like a precision carving method where chemical agents infiltrate the biomass precursor and begin modifying the internal framework before heat completes the transformation. These agents reduce tar formation, preserve pore entrances, and promote the formation of micropores even at lower temperatures than those required for physical activation (Umar *et al.*, 2025). Acidic agents such as H_3PO_4 promote dehydration and cross-linking, generating micropores, and creating oxygen-containing surface groups, whereas alkaline agents such as KOH and NaOH induce redox pathways that enlarge the carbon lattice and generate abundant microporosity (Dobele *et al.*, 2024). Salt-based activation, particularly with $ZnCl_2$, promotes early charring and uniform penetration into the carbon matrix, resulting in a broader distribution of pore sizes (Umar *et al.*, 2025). The strength of chemical activation lies in its ability to produce well-developed pore networks, high carbon yields, and uniformly modified surfaces (Kundu *et al.*, 2024). However, corrosive chemicals require careful handling, leave residues that demand thorough washing, and may impose environmental burdens if not properly recovered or neutralised.

Table 3 presents a systematic comparison of commonly used physical and chemical activating agents for biomass-derived carbon materials, linking their activation mechanisms to pore development characteristics and resulting CO_2 capture performance. Moreover, the performance differences between these strategies are evident in Figure 3, which shows that chemical activation generally produces higher surface area, greater pore volume, and superior CO_2 adsorption capacity relative to physical activation.

Table 3: Systematic comparison of common activating agents used for biomass-derived carbon materials for CO_2 capture

Activating Agent	**Activation Type**	**Primary Role in Pore Development**	**Typical Pore Structure**	**CO_2 Capture Performance**	**Advantages**	**Limitations**
CO_2	Physical	Gasification of carbon matrix	Microporous	Moderate	Simple, low cost, environmentally benign	Requires high temperature, lower surface area
Steam	Physical	Aggressive carbon etching	Micro-mesoporous	Moderate-high	Fast pore development, high surface area	Lower carbon yield, pore collapse risk
KOH	Chemical	Redox intercalation and lattice expansion	Ultra-microporous	High	Highest CO_2 uptake at low pressure	High chemical use, wastewater generation
NaOH	Chemical	Similar to KOH but less aggressive	Microporous	High	Lower cost than KOH	Slightly lower performance
H_3PO_4	Chemical	Dehydration and cross-linking	Micro-mesoporous	Moderate	High carbon yield, lower activation temperature	Residual phosphorus, limited ultra-micropores
$ZnCl_2$	Chemical	Early charring and pore stabilisation	Micro-mesoporous	Moderate-high	Uniform pore distribution	Toxicity concerns, recovery required

Source: Singh *et al.* (2019); Dissanayake *et al.* (2020); Goel *et al.* (2021)

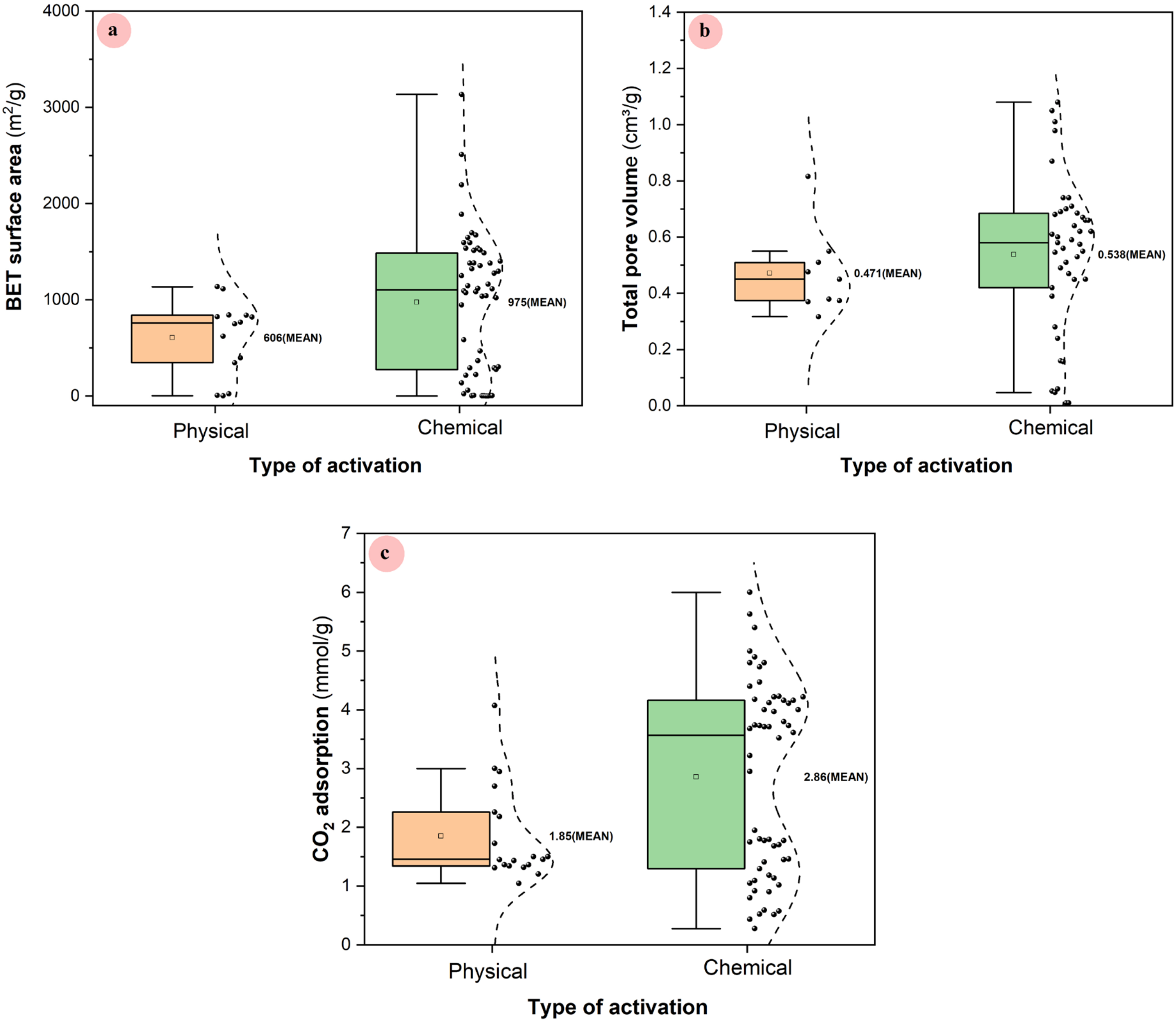

Figure 3: Comparative performance of physical and chemical activation for biomass-derived carbon in (a) BET surface area, (b) total pore volume, and (c) CO_2 adsorption capacity
Source: Dissanayake *et al.* (2020); Goel *et al.* (2021)

Economic and Environmental Implications

Economic and environmental evaluations are central to determining the feasibility of biomass-derived carbon materials for carbon capture. Life-cycle assessment, a standardised framework, quantifies environmental impacts from resource extraction to end-of-life treatment and is routinely used to assess energy use, emissions, and resource flows in carbon material production.

Recent studies reveal that activation intensity, chemical use, and washing requirements significantly influence the final environmental footprint, with chemical activation often resulting in higher embodied impacts due to reagent production and wastewater treatment requirements (Saleem *et al.*, 2025). Techno-economic analysis evaluates cost distribution, capital requirements, and economic competitiveness, providing indicators such as net present value and minimum selling price. It complements sustainability assessment by determining whether biomass-derived carbon pathways are financially viable for large-scale implementation and by identifying key cost drivers that influence their feasibility. Capital costs typically include gas-solid contactors, adsorption–desorption columns, regeneration units, and flue gas conditioning systems, which scale with plant capacity and site-specific infrastructure. Operating costs further include sorbent makeup, regeneration energy, labour, and maintenance, with reagent expenses in chemically activated systems often accounting for more than half of total operating expenditures (Patel *et al.*, 2024).

From an environmental standpoint, biomass-derived carbons can offer substantial reductions in greenhouse emissions compared to synthetic adsorbents such as amine-based sorbents or metal-organic frameworks. It should be noted that activated carbons from waste biomass often achieve net negative or near-neutral emissions when process energy is sourced from biomass residues or renewable electricity (Senadheera *et al.*, 2024). A separate study demonstrated that a KOH- or NaOH-activated carbon from coconut shell biomass exhibits lower net carbon emissions per kg of sorbent than comparable commercial activated carbon, particularly when functional performance (adsorption capacity) is accounted for (Saleem *et al.*, 2025). The activation route strongly affects environmental outcomes: Chemical activation often requires significant chemical reagent production and wastewater treatment, thereby increasing upstream impacts relative to physical activation.

From an economic standpoint, the cost-effectiveness of producing carbon materials from biomass is strongly shaped by how readily the feedstock can be sourced and how efficiently the conversion process operates. In systems that rely on inexpensive lignocellulosic residues such as woodchips and emphasise low-energy, self-sustained carbonisation, the financial performance improves significantly (Samsudin *et al.*, 2025). Physical activation methods such as steam or CO_2 activation, are often more economically favourable at larger scales because they avoid reagent costs and can leverage existing energy infrastructure (Banerjee *et al.*, 2024). In contrast, chemical activation incurs higher operating expenses due to reagent consumption. Still, it may partially offset these costs by increasing adsorption capacity and reducing sorbent replacement frequency, thereby lowering the cost per unit of CO_2 captured. Table 4 presents recent studies on biomass-derived carbon for carbon capture, highlighting its economic and environmental benefits.

Table 4: Recent studies on economic and environmental implications of biomass-derived carbon material for carbon capture, summarising their methodologies and major findings

Feedstock	Synthesis/Activation Method	Operating Conditions	Assessment Type	Key Findings	References
Persian ironwood biomass	- Chemical activation using H_3PO_4 to synthesise activated carbon - Steps: Grinding, mixing with H_3PO_4, drying, pyrolysis, washing, drying, sieving	- Two-stage AC production: (1) Carbonisation yield 50% (2) Activation yield 44% - Pyrolysis under inert gas (N_2) - Regeneration at 250°C for 2 hours under dynamic vacuum	Environmental and economic	- AC demonstrates a substantially lower life-cycle burden, with H_3PO_4 dominating impact hotspots, while modified AC suffers from significantly higher energy demand and toxicity potentials due to copper-based modification - Despite modest economic returns for both materials, modified AC's elevated impacts outweigh its performance gains, indicating limited sustainability justification for metal-assisted activation	Nowrouzi *et al.* (2021)
Mixed food waste	- Two-step process: (1) Carbonisation (slow pyrolysis) to obtain FW400 (2) Chemical activation with KOH at various ratios and temperatures to obtain engineered biochar FW400-KOHx(y)	- Carbonisation: 400°C for 1 hour - Activation: (1) KOH/FW400 mass ratio 1:3 (2) Temperature 500°C to 800°C for 1 hour - Drying: 110°C for 24 hours - CO_2 adsorption tests: 0°C, 25°C, and 50°C up to 1 bar - Cyclic stability: 5 cycles, adsorption at 25°C, desorption at 150°C for 12 hours	Environmental	- The engineered food-waste biochar FW400-KOH600(2) shows competitive CO_2 uptake driven by ultra-micropore formation, yet its environmental performance is constrained by the intensive KOH activation stage, which contributes the majority of upstream impacts - While the cradle-to-grave carbon balance becomes negative due to biogenic carbon sequestration, the process still relies on energy- and chemical-demanding steps that limit practical deployment	Yuan *et al.* (2022)

Bamboo sawdust	- Pyrolysis is followed by KOH activation to produce bamboo biochar with high porosity	- Carbon precursor carbonised near 1,000ºC - KOH ratio 1:1 - Activation under nitrogen flow at 10ºC per minute to 700ºC with 1 hour holding time - Post-treatment with dilute hydrochloric acid and deionised water, followed by drying at 105ºC	Economic	- KOH activation produces a porous carbon material with an enlarged specific surface area that promotes strong physisorption of CO_2. The material reaches an uptake of 1.50 mmol/g at 25ºC under 15% CO_2 and full regeneration at 80ºC - Techno-economic analysis of a solar-driven adsorption system shows reductions in carbon emission intensity and levelised electricity cost with a removal cost of 14.12 USD/tCO_2, which is superior to monoethanolamine and polyethyleneimine silica due to lower regeneration energy and reduced capital requirement	Ji *et al.* (2022)

Policy and Practical Implications

The advancement of biomass-derived carbon sorbents presents a timely opportunity for policymakers seeking scalable, low-carbon solutions to support national and international climate commitments. Because these materials can be sourced from abundant agricultural and forestry residues, while offering competitive adsorption performance and lower regeneration energy requirements, they align strongly with the decarbonisation objectives embedded in emerging carbon management frameworks. However, realising their full potential requires coordinated policy support that addresses economic barriers, standardisation gaps, and deployment bottlenecks across the carbon-capture value chain.

From a regulatory standpoint, governments should prioritise incentives that reward the use of waste biomass and low-emission activation pathways. Production routes that use self-sustaining carbonisation, steam, or CO_2 activation significantly reduce upstream emissions and operational costs compared with reagent-intensive chemical activation. Targeted policies such as tax credits for renewable sorbent manufacturing, feed-in incentives for using agricultural residues, or subsidies that offset the capital cost of activation units would accelerate the transition from laboratory-scale sorbent development to commercial production. In parallel, integrating biomass-derived carbons into national carbon accounting and carbon credit schemes would enhance their market viability by recognising their near-neutral or even negative life-cycle emissions.

Policy frameworks should also emphasise standards and certification mechanisms for sorbent sustainability. Because environmental burdens vary widely depending on feedstock selection, activation route, and energy sourcing, transparent certification (e.g., low-carbon material labelling, waste-to-sorbent traceability) would allow industries to adopt biomass carbons while confidently maintaining compliance with net-zero targets. Standardisation would further help utilities and industrial emitters evaluate sorbent options in procurement processes, bridging the gap between academic performance reporting and real-world operational requirements.

Biomass-derived carbon capture occupies a unique and strategic position within the portfolio of negative emissions technologies, as it directly aligns with the principles of Bioenergy with Carbon Capture and Storage (BECCS). Unlike fossil-based capture systems that primarily reduce emissions, biomass carbon capture enables net atmospheric CO_2 removal by coupling biogenic carbon uptake during biomass growth with durable carbon capture and storage or utilisation pathways. When biomass-derived carbon materials are integrated into capture-regeneration or capture-utilisation systems and evaluated across their whole life cycle, they offer a scalable, modular, and resource-efficient route toward BECCS deployment, particularly in decentralised and biomass-rich regions. From a policy perspective, the commercialisation of biomass-based carbon capture technologies would be strongly accelerated by differentiated subsidy frameworks that explicitly target negative emissions technologies. Establishing higher credit prices or tailored incentives for verified net-negative CO_2 removal, rather than uniform carbon pricing, would more accurately reflect the societal value of BECCS and provide a decisive economic signal for large-scale implementation of biomass-derived carbon capture systems.

Challenges and Perspectives

Despite the promising performance and sustainability advantages of biomass-derived carbon sorbents, several critical challenges must be addressed before they can be widely deployed in integrated carbon capture systems. A primary limitation lies in scaling production capacity. Although biomass residues are plentiful, consolidating them into reliable, year-round supply chains is complex and requires alignment between agricultural producers, waste management sectors, and industrial users. Variability in biomass quality, transportation costs, and seasonal availability further constrain large-scale manufacturing. Establishing pilot-scale and regional production hubs, especially in rural areas where residues are concentrated, will be essential for generating operational data, validating material consistency, and assessing techno-economic performance under realistic conditions.

A second challenge concerns integration with existing capture infrastructure. While the tunability of biomass-derived carbons enables tailoring pore structures and surface functionalities for specific flue gas profiles, real industrial conditions introduce complexities, including contaminants, high humidity, variable temperatures, and repeated adsorption–desorption cycling. These factors can influence sorbent stability, regeneration efficiency, and long-term performance. Another key barrier involves the energy intensity of activation and regeneration processes. Although physical activation routes such as steam or CO_2 activation are more sustainable than chemical activation, they still require significant thermal input. Integrating renewable heat, biomass residues, or waste-heat recovery systems into activation processes can substantially reduce life-cycle emissions. Embedding sorbent production into national clean-energy incentives or industrial decarbonisation strategies would support this transition and strengthen the environmental competitiveness of biomass-derived adsorbents.

Concluding Remarks

This review article provides a comprehensive and integrative assessment of biomass-derived carbon materials for carbon capture, distinguishing itself from the existing literature by systematically linking formation mechanisms, synthesis routes, activation strategies, and sustainability metrics within the context of integrated carbon capture systems. Unlike prior reviews that predominantly focus on either adsorption performance or material synthesis in isolation, this work consolidates mechanistic understanding with comparative techno-economic and life-cycle perspectives, thereby offering a more holistic evaluation of material viability for large-scale deployment. In particular, the review emphasises the interplay between HTC and pyrolysis as complementary synthesis routes, highlights the decisive role of activation chemistry in governing pore architecture and CO_2 selectivity, and synthesises quantitative trends in adsorption performance across activation pathways.

Beyond summarising state-of-the-art performance, this review critically evaluates economic and environmental trade-offs associated with different activation strategies and feedstock choices. By systematically comparing physical and chemical activation agents and integrating life-cycle assessment and techno-economic analysis, the article advances the discussion from laboratory-scale optimisation toward realistic implementation scenarios. The inclusion of comparative tables and synthesis–performance–sustainability linkages further differentiate this review from previous studies that lack structured cross-domain analysis.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Conflict of Interest Statement

The author declares no conflict of interest.

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