

Tackling climate and industrial challenges: Sustainable porous carbon materials for CO₂ mitigation and applications

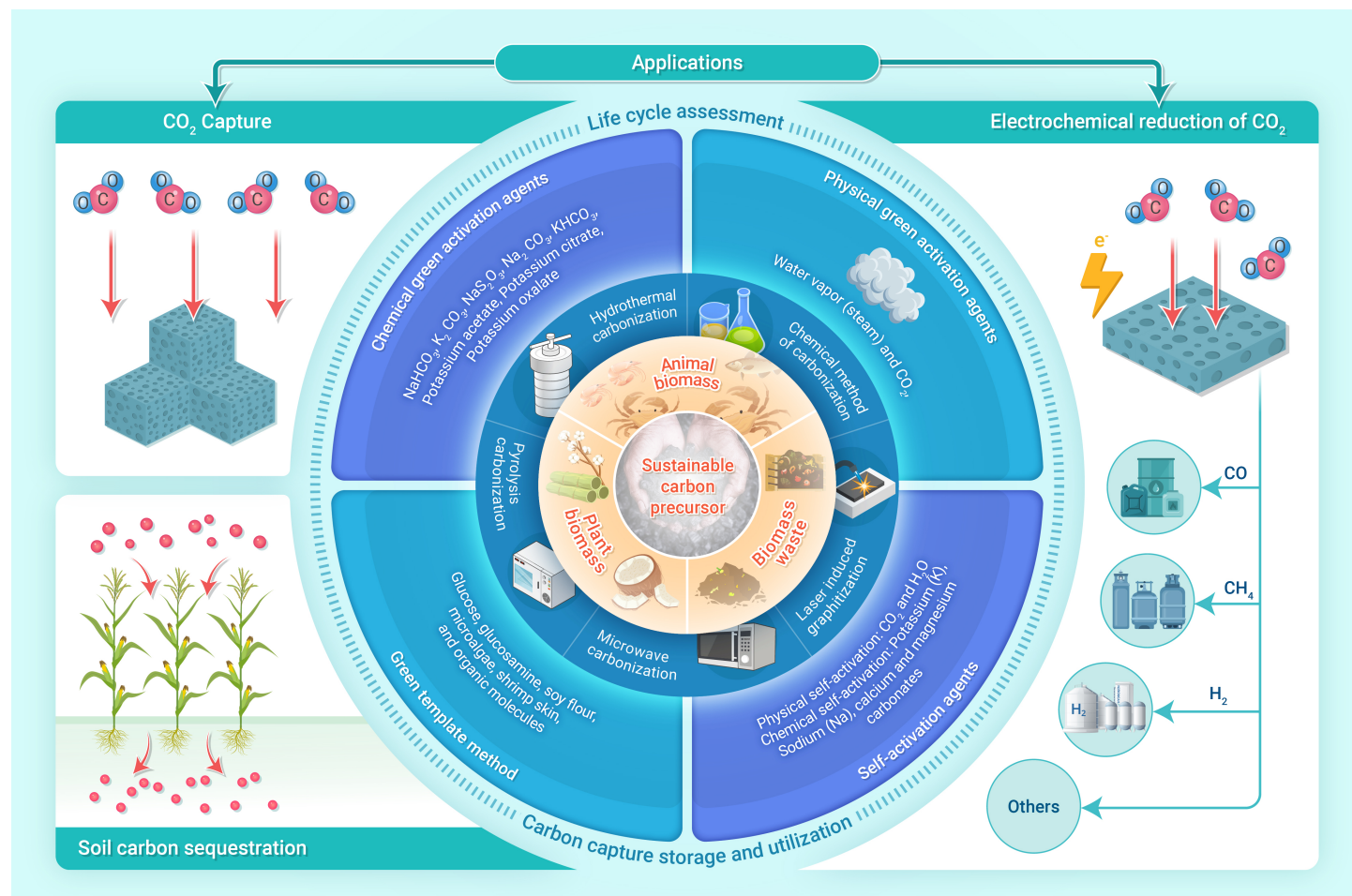
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Sustainable porous carbon materials (PCMs) from renewable precursors with low carbon emissions.
- Energy-efficient carbonization and green activation lower environmental impacts and costs.
- Life cycle assessment guides eco-friendly PCM design for CO₂ capture, conversion, and utilization.

Tackling climate and industrial challenges: Sustainable porous carbon materials for CO₂ mitigation and applications

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The escalating climate crisis necessitates a shift towards sustainable practices in synthesizing and utilizing porous carbon materials (PCMs), which are vital for CO₂ capture and utilization. However, traditional PCMs synthesis often involves fossil fuel-derived precursors, energy-intensive processes, and hazardous agents, raising environmental concerns. This review focuses on sustainable PCMs strategies with low carbon emissions, emphasizing renewable precursors like biomass and waste biochar as alternatives to fossil fuels. It also explores energy-efficient carbonization techniques and green activation methods, highlighting pathways to environmentally benign PCMs synthesis. A dedicated life cycle assessment section offers a comprehensive view of the environmental impact from inception to disposal. The review also examines the applications of PCMs in carbon capture and storage, addressing challenges and future prospects. This critical analysis serves as a roadmap for researchers and practitioners aiming to develop low-carbon-emission materials and advance PCMs synthesis in line with environmental sustainability.

INTRODUCTION

The relentless rise of global warming, driven by the continuous emission of greenhouse gases, primarily carbon dioxide (CO₂), from various sectors—especially power and industrial sectors—has elevated climate change to a critical environmental concern.¹ Since the Industrial Revolution began in 1750, atmospheric CO₂ concentrations have significantly increased, with the current level reaching 410 parts per million (ppm).² This rise in CO₂ is mainly attributed to fossil fuel combustion and deforestation, both of which contribute substantial amounts of CO₂ into the atmosphere. The International Panel on Climate Change (IPCC) projects that if current trends persist, atmospheric CO₂ concentrations could soar to 570 ppm by the year 2100.³ This sharp rise is expected to cause a global temperature increase of approximately 1.9°C, with potentially devastating environmental consequences, including increased drought frequency and severity, altered rainfall patterns, intensified heatwaves, accelerated glacier melting, and rising global sea levels.⁴ These changes will have profound impacts on ecosystems, agriculture, and human societies. To confront this growing crisis, it is crucial to develop sustainable methods for capturing and storing CO₂. These strategies are essential for mitigating CO₂ emissions and combating global warming, as emphasized in the fifth assessment report by the IPCC.³ Scientific research and innovation are pivotal in efforts to address this urgent global challenge. Among the emerging solutions, carbon capture and sequestration (CCS) technologies have gained prominence.⁵ Within this field, adsorption stands out as a cost-effective and highly efficient method for CO₂ capture and storage. Several materials, including carbonaceous substances, zeolites, metal-organic frameworks (MOFs), covalent organic frameworks (COFs), and porous organic polymers (POPs), have shown promise as CO₂ adsorbents.^{6–11} Zeolites, however, are highly sensitive to moisture, temperature, and pressure, while MOFs, despite their potential for enhanced selectivity via specific metal incorporation, face challenges in terms of cost, complexity, and moisture sensitivity, which can compromise their structural integrity during CO₂ adsorption.¹²

PCMs offer a competitive advantage in CO₂ capture compared to non-

carbon-based adsorbents. Sourced from a wide range of cost-effective resources, PCMs are simple to prepare and offer excellent controllability, making them practical for industrial use. These materials exhibit high specific surface areas, tunable porosity, and chemical versatility, and their moisture insensitivity ensures stability during CO₂ uptake.^{13–16} Almaz et al.¹³ synthesized asphalt-derived porous carbon containing H₂O in the pore space, achieving a surface area of 4200 m² g^{−1} and a high CO₂ uptake capacity of 48 mmol g^{−1}. However, conventional PCMs typically rely on fossil fuel-derived precursors, such as asphalt, ethylene, methane, and polyacrylonitrile (PAN), raising sustainability concerns. These sources are finite and contribute significantly to greenhouse gas emissions, exacerbating the climate crisis.

Thus, developing PCMs from sustainable resources is essential for advancing CO₂ capture technology. The first step toward sustainable PCMs synthesis is selecting low-carbon-emission carbon precursors. Biomass-derived precursors provide a renewable, sustainable alternative to fossil fuel-based sources, offering low cost, extensive availability, and ease of access.^{17–19} Plant-based biomass, such as agricultural residues and forestry waste, serves as a rich carbon source,^{18,19} while animal-derived biomass, including manure and waste keratin, provides a valuable opportunity for utilizing waste streams.^{20,21} Biomass waste, in particular, stands out as a valuable carbon resource, offering environmental benefits.^{22–24} For example, Wang et al.²⁵ treated plastic polyethylene terephthalate with different agents under varying carbonization temperatures. The sample treated with KOH at 900°C exhibited a high specific surface area of 3090 m² g^{−1} and a CO₂ uptake capacity of 6.23 mmol g^{−1}. Unfortunately, much of this solid biomass waste is currently disposed of through environmentally harmful methods like landfilling or incineration. These methods not only pollute the environment but also waste a precious resource that could be transformed into high-value functional carbon materials.^{26,27}

Carbonization is a crucial step in converting carbon precursors into PCMs, but traditional methods can be energy-intensive and contribute to greenhouse gas emissions. To reduce the environmental impact of PCMs synthesis, energy-efficient techniques such as hydrothermal carbonization (HTC) are emerging as promising alternatives. HTC involves treating biomass precursors with water at moderate temperatures (180–265°C) and pressures (up to 6.0 MPa), resulting in PCMs with tailored properties.^{28–30} Other methods, including pyrolysis carbonization,^{30,31} laser-induced graphitization,^{32,33} and microwave-assisted carbonization,^{22,34} also hold promise for energy-efficient carbonization. Green activation agents and templates,^{35,36} offer an environmentally friendly approach to modifying PCMs with enhanced properties. Life cycle assessment (LCA) is essential for evaluating the overall environmental impact of PCMs, considering their entire life cycle from raw material extraction to disposal.³⁷ LCA can identify environmental hotspots and guide the development of truly sustainable PCMs. The selection of biomass feedstock is critical, as different sources have varying carbon content, energy requirements, and processing implications. Therefore, careful consideration of biomass sources and manufacturing methods is crucial to minimizing the carbon footprint of PCMs production.³⁸

This review explores the development and utilization of sustainable PCMs as a key step in mitigating climate change while supporting industrial growth. By summarizing the environmental impact of PCMs and emphasizing

Table 1. A comparison of carbon footprint emissions between conventional and biomass-incorporated sintering processes.³⁹

Process	CO ₂ (kg)	CO (kg)	NO _x (kg)	SO _x (kg)	Total
Conventional Sintering	200	19.5	0.59	2.02	222.11
Modified Sintering ^a (70:20:10)	188.08	18.33	0.50	1.60	208.52
Modified Sintering ^b (70:30)	195.56	19.06	0.54	1.64	216.80
Modified Sintering ^c (90:10)	190.92	18.60	0.54	1.85	211.92

a: 70:20:10 refers to Coke (CB): Charcoal (CH): Sawdust (SD). b: 70:30 refers to Coke: Charcoal. c: 90: 10 refers to Coke: Sawdust.

Table 2. A cost inventory comparison of the conventional (coal-based) and modified (biomass-based) sintering processes.³⁹

Constituents	Price/tonne	Price/tonne (100% Coke)	Price/tonne (100% Sawdust)	Price/tonne (100% Charcoal)
Iron Ore	2238 (fines) 3646 (lumps)	1309	1202	1202
Lime	6000	68	318	318
Limestone	928	40	44	44
Bentonite	2000	6	6	6
Fuel	30,000 ^a	1800	240b	720c
Dolomite	1275	22	26	26
Return Fines	2238	627	627	627
Total	–	3872	2463	2943

a: Price of coke: 30000/t. b: Price of sawdust: 4000/t. c: Price of charcoal: 12000/t.

sustainable carbon precursors, energy-efficient carbonization techniques, and LCA frameworks, this review aims to accelerate the development of PCMs with immense potential in CO₂ capture, conversion, and utilization, ultimately contributing to a greener, more sustainable future.

STRATEGIES TO PREPARE SUSTAINABLE PCMs WITH LOW CARBON EMISSION

Sustainable carbon precursors with low carbon emissions focus on developing and utilizing environmentally friendly, renewable carbon source materials that produce minimal carbon dioxide during production. This approach addresses climate change by reducing the carbon footprint associated with traditional carbon precursor manufacturing processes. There is a necessity to create more sustainable versions of conventional carbon materials with low emissions, promoting a circular carbon economy and an environmentally conscious future. Gaurav et al.³⁹ discussed the comparison of carbon footprint and cost reduction between traditional coke-carbonization and biomass-carbonization. A 10% cost reduction and approximately 6% reduction in CO₂ emission were achieved. Detailed information is provided in Table 1 and Table 2. In this section, we will discuss various carbon precursors that significantly contribute to CO₂ emission reduction, offering sustainable alternatives to conventional fossil fuel-derived sources.

Biomass-based carbon precursors

Biomass, organic material from plants and animals, is a renewable resource used to produce PCMs with low carbon emissions.⁴⁰ As defined by the International Energy Agency, biomass is biological material created through photosynthesis, directly or indirectly. It includes organic materials from forestry, agriculture, households, livestock farming, and associated wastes and residues. Economically advantageous due to its predominantly waste-based nature, biomass offers several benefits over fossil fuels: it is renewable, and its carbon material production typically results in fewer greenhouse gas emissions. Biomass precursors can be categorized into three main groups: plant biomass (small molecules like glucose and fructose, and larger ones like cellulose, hemicellulose, and lignin),⁴¹ animal-derived biomass, which includes organic residues and byproducts,⁴² and biomass waste, derived from both plants and animals.⁴² These materials are crucial in sustainable industrial processes, serving as starting points for producing various biomass-based carbon materials. Figure 1 in this review outlines the

primary categories of biomass sources for sustainable carbon precursors, to be further examined in the following sections.

Plant biomass-based PCMs

Cellulose. Cellulose, the most abundant plant macromolecule, comprises up to half of their carbon content.⁴³ It is crucial for plant cell wall integrity, with its structure formed by hydrogen bonds and van der Waals interactions, giving it exceptional strength. Cellulose, composed of glucose units with molecular weights ranging from 50,000 to 2,500,000, is widely used as a precursor for carbon materials. Common cellulose sources include commercial cellulose and that extracted from lignocellulose via sulfite and alkali extraction.^{44–45} Pyrolysis, a key method for converting cellulose into carbon materials, involves heating biomass without oxygen, breaking down organic molecules into carbon-rich compounds. Fan et al. studied how heating rates affect cellulose functional groups during pyrolysis, noting changes in -OH, =C-H, and C=O bonds with temperature variations.⁴⁶ Gao et al. utilized a simple pyrolysis method with O₂-NH₃ reactivity to create conductive, porous carbon paper from cellulose fibers.⁴⁷

Wang et al. developed an innovative low-temperature method (90°C) for converting cellulose nanofibers (CNF) into highly graphitized carbon structures using sulfuric acid in an oxygen-free environment, significantly reducing carbon emissions compared to traditional pyrolysis, as depicted in Figure 2A.⁴⁸ Lai et al. introduced a bottom-up approach for fabricating anisotropic carbon aerogels with a 3D lamellar structure, utilizing directional freezing, freeze-drying, and carbonization, as shown in Figure 2B.⁴⁹ These cellulose nanofiber-based aerogels are highly porous, lightweight, and conductive. Vazhayal et al. produced carbon aerogels from waste tissue paper and polyvinyl alcohol (PVA), achieving a unique 3D hierarchical porous structure with a high specific surface area⁵⁰ (Figure 2C). Typha Orientalis (TO) biomass-derived carbon aerogels, characterized by super-hydrophobicity and significant surface area, were synthesized by another group (Figure 2D).⁵¹ Additionally, a study on sunflower receptacles and stalks as precursors produced porous carbon aerogels with a surface area of up to 3072 m²/g, demonstrating high efficiency in adsorbing CO₂, iodine, and contaminants from water (Figure 2E).⁵²

Hemicellulose. Hemicellulose, a key component of lignocellulosic biomass (25–35%), has emerged as a sustainable precursor for low-carbon-emission carbon materials.⁵³ Unlike cellulose, hemicellulose is amorphous, consisting

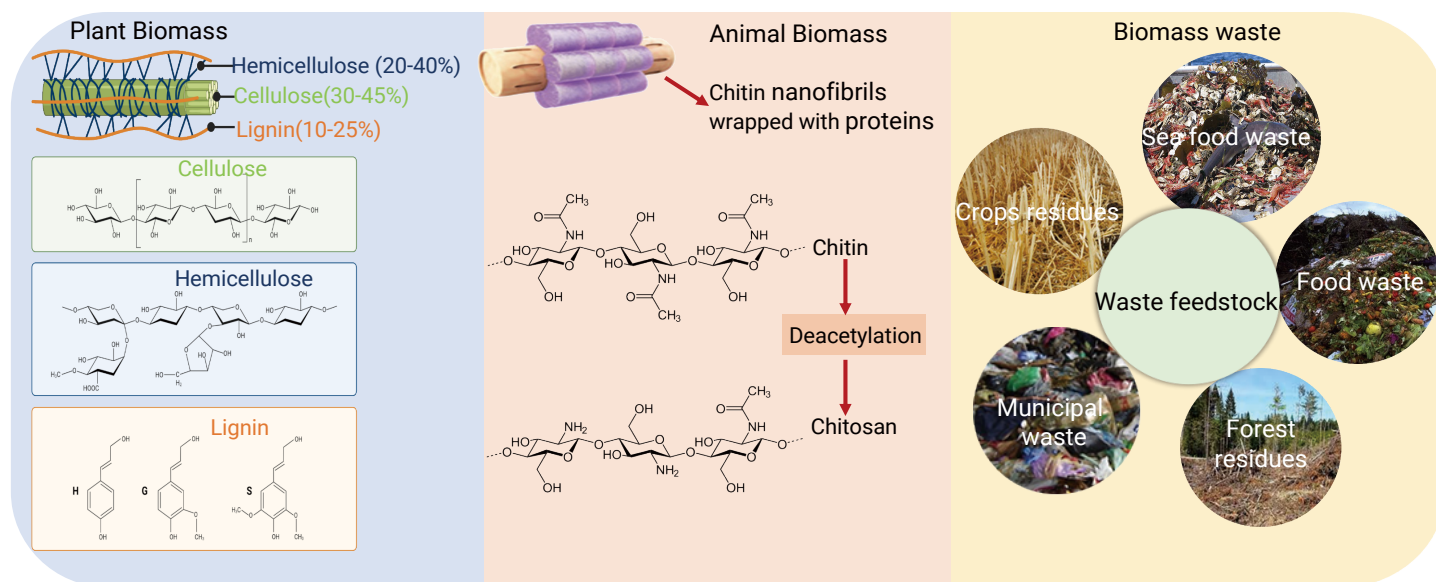


Figure 1. Summary of the typical primary categories of sustainable biomass sources, including plant biomass, animal biomass, and biomass waste as renewable feedstocks with a low carbon footprint.

of diverse polysaccharides like pentoses, hexoses, and hexuronic acids.^{54–55} Its lower degree of polymerization gives it unique characteristics, making it suitable for producing distinct carbon products. Hemicellulose is typically extracted from biomass via alkali treatments.⁵⁶ Wang et al. transformed hemicellulose from hemp stems into carbon materials using a low-temperature hydrothermal carbonization (HTC) process with KOH activation, resulting in carbon materials with a spherical morphology and a high specific surface area of 3062 m²/g.⁵⁷ This method reduces energy consumption and carbon emissions. Similarly, Lin et al. extracted hemicellulose from pomelo peel, carbonizing it with zinc chloride activation to create a PCMs with a specific surface area of 1361 m²/g.⁵⁸ As shown in Figure 2F, these studies highlight hemicellulose's potential in creating carbon materials while minimizing carbon emissions through innovative, low-temperature processes.

Lignin. Lignin, a complex and abundant organic polymer, is gaining attention as a sustainable precursor for PCMs due to its high carbon content (42–60%) and availability as a byproduct of the paper and biorefinery industries, with an annual global production of about 70 million tons.^{59–60} Its high carbon content contributes to cost-efficiency in PCMs production.⁶¹ The chemical structure of lignin, with its intricate three-dimensional network of phenolic compounds, allows for tailoring carbon materials with desired properties such as porosity, surface area, and conductivity.^{58,62} Lignin-based carbon precursors are appealing for minimizing carbon footprints due to their potential for lower-temperature carbonization.

Sansi et al. demonstrated the successful preparation of amine-functionalized lignin-derived mesoporous carbons, highlighting their unique three-dimensional interconnectivity and enhanced CO₂ adsorption capabilities.⁵³ Additionally, Zhao et al. synthesized lignin-based porous supraparticles with high surface area and micropores (200 nm to 2.3 μm), converting them into nonfusible carbon nano- and microspheres through a two-step process of oxidative thermostabilization followed by carbonization.⁶⁴ As shown in Figure 2G, this method provides an efficient and sustainable approach to carbon sequestration, aligning with current efforts in developing eco-friendly materials.

Glucose and Fructose. Glucose has gained significant attention as a sustainable carbon precursor due to its abundance as the most common natural monosaccharide and its biodegradability. Glucose serves as a building block for polysaccharides like starch and cellulose, making it an attractive renewable source for carbon materials. Its use as a carbon precursor is environmentally friendly, minimizing carbon emissions. Zhang et al. developed a scalable method for producing high-quality graphene using glucose, with FeCl₃ serving as both template and catalyst, as shown in Figure 2H.⁶⁵ This process involves dissolving glucose and FeCl₃ in water, followed by calcina-

tion at 700°C, resulting in graphene sheets with minimal layers and high electrical conductivity (768 S m⁻¹). The method significantly reduces carbon emissions compared to conventional techniques like chemical vapor deposition (CVD).⁶⁶

Fructose, an isomer of glucose, has also emerged as a valuable low-carbon emission carbon source, especially for metal nanoparticle support. With a lower carbonization temperature (130°C compared to glucose's 150°C).⁶⁷ Fructose has been used to synthesize carbon shells around silver nanoparticles via HTC, stabilizing the nanoparticles and minimizing damping effects on plasmon resonance.⁶⁸ Fructose-derived carbon supports can be functionalized to enhance performance, as demonstrated by Mahyari et al., who improved the stability and reduced leaching of Au nanoparticles through thiol functionalization.⁶⁷ Additionally, Kurniawan et al. produced environmentally sustainable graphene quantum dots (GQDs) using fructose in a microplasma-assisted process under ambient conditions, yielding GQDs with an average size of 4.5 ± 1.7 nm.⁶⁹ These developments highlight fructose's role in advancing sustainable material synthesis with reduced carbon emissions.

Animal biomass-based PCMs

Animal biomass, rich in complex components, offers valuable sources for PCMs preparation. Chitin, the second most abundant biopolymer after cellulose, is primarily found in the cuticles of arthropods and crustacean shells, as well as fungi cell walls. It boasts a significant 36.43% content in shrimp shells.^{70–71} Chitin's strong intermolecular hydrogen bonding renders it insoluble in water and alkali solutions. Its applications extend to biomedical fields, including wound dressings⁷² and suture.⁷³ Given the large amounts of seafood waste produced annually, chitin holds great potential for sustainable development. For instance, Xu et al. developed fibrous carbon microspheres (FCMs) from chitin, which showed promising CO₂ adsorption capabilities (Figure 2I).⁷⁴ Dassanayake et al. produced activated carbon from chitin aerogels with high specific surface area and microporosity, indicating potential for environmental applications.⁷⁵ Despite its abundance, chitin remains underutilized for PCMs synthesis, highlighting the need for further research, particularly for CO₂ mitigation.

Chitosan, derived from chitin, is nitrogen-rich, biodegradable, and has high adsorption capacity, making it an excellent precursor for CO₂ adsorbents. The global market for chitosan is expected to grow significantly, reflecting its potential as a sustainable alternative.⁷⁶ Chitosan is primarily sourced from shrimp shells due to their lower calcium carbonate content and higher chitin content compared to other crustaceans.⁷⁷ Yang et al. developed N-doped porous carbons (NPCs) from chitosan using an environmentally friendly

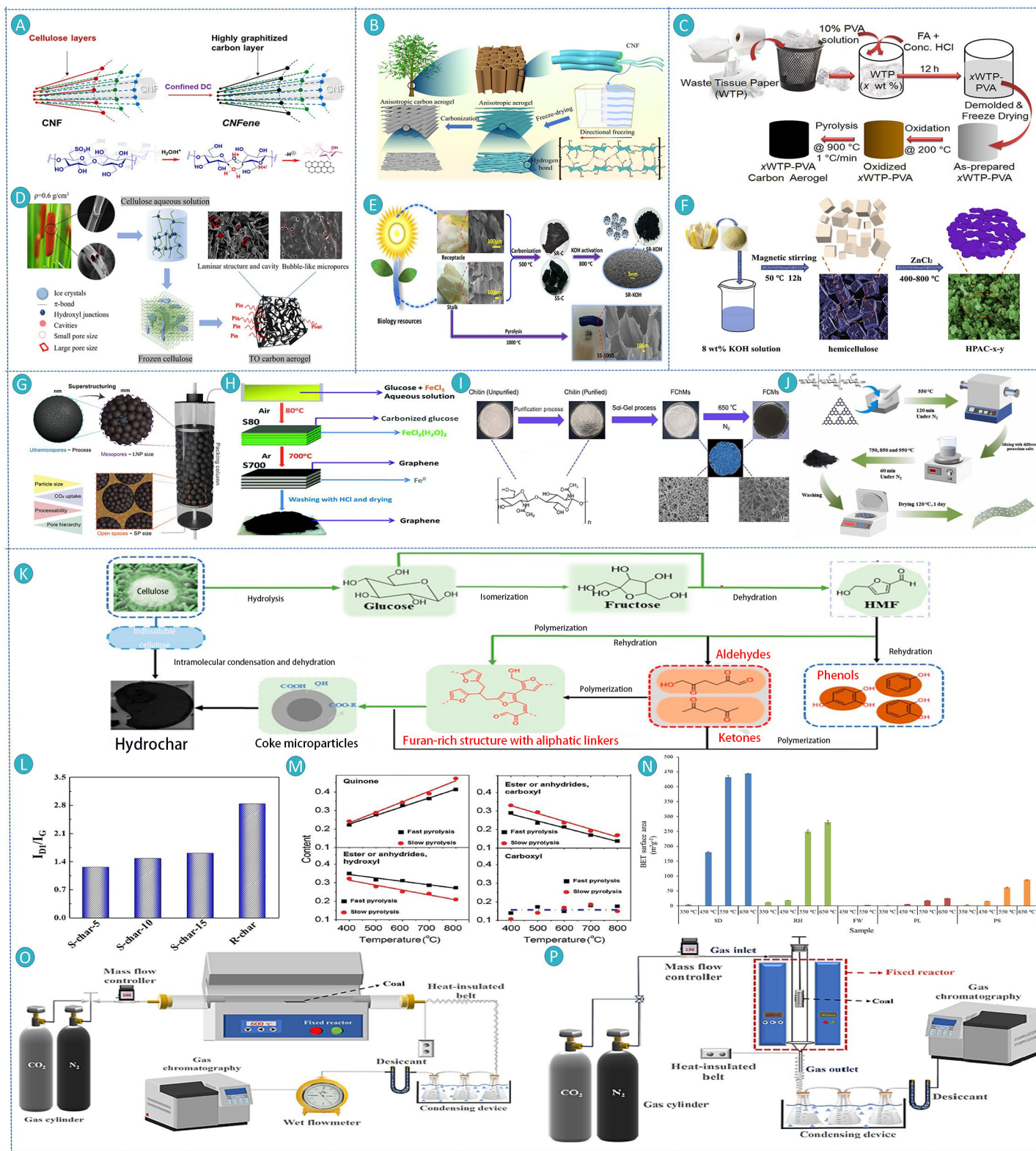


Figure 2. Energy efficient carbonization of biomass for sustainable PCMs (A) Schematic of CNF extraction and carbonization into graphitized carbon.⁴⁸ Copyright 2021, American Chemical Society. (B) Fabrication and structure of CNF carbon aerogels through directional freezing, freeze-drying, and carbonization.⁴⁹ Copyright 2021, American Chemical Society. (C) Preparation of xWTP-PVA CAs.⁵⁰ Copyright 2020, Elsevier. (D) TO cellulose extraction using acid treatment, followed by freeze casting, drying, and carbonization.⁵¹ Copyright 2023, Elsevier. (E) Porous carbons from spongy plant flesh.⁵² Copyright 2019, Elsevier. (F) Simplified synthesis of porous activated carbon from hemicellulose.⁵⁸ Copyright 2020, Elsevier. (G) Hierarchical porous carbons from lignin.⁵⁴ Copyright 2021, American Chemical Society, under CC BY license. (H) Graphene sheets via carbonization and calcination of glucose and FeCl₃.⁶⁵ Copyright 2014, Royal Society of Chemistry. (I) Fibrous carbon microspheres from chitin.⁷⁴ Copyright 2022, Elsevier, under CC BY license. (J) Nitrogen-doped microporous carbon nanosheets from chitosan.⁷⁹ Copyright 2022, Elsevier. (K) The mechanism diagram of hydrothermal carbonization.¹¹² Copyright 2025, MDPI, under CC BY license. (L) I_{D1}/I_G ratios indicating carbon structure defects at different pyrolysis rates.¹²⁷ Copyright 2021, Elsevier. (M) XPS spectra showing heating rate effects on functional groups.¹²⁸ Copyright 2020, Elsevier. (N) BET surface area of biochars at different temperatures.¹²⁹ Copyright 2020, Elsevier. Schematic of pyrolysis systems: (O) Slow pyrolysis and (P) Fast pyrolysis.¹³⁰ Copyright 2023, Elsevier.

method that avoids toxic solvents.⁷⁸ Li et al. synthesized N-doped micropore-dominated carbon nanosheets from chitosan using potassium salts as acti-

vators, demonstrating the potential for green adsorbent design (Figure 2J).⁷⁹ Additionally, optimized chemical activation of chitosan with KOH and urea produced nitrogen-doped PCMs with high surface area and ultra-microporosity.⁸⁰ Hierarchical porous nitrogen-containing activated carbons (N-ACs) were synthesized from chitosan using a LiCl–ZnCl₂ molten salt template, resulting in high surface area and excellent CO₂ capture capabilities.⁸¹ Another method using acetic acid and varying activator ratios created chitosan-based porous carbons with ultra-high specific surface areas and microporosity, contributing to circular economy efforts and climate change mitigation.⁸²

BIOMASS WASTE: A TREASURE TROVE OF SUSTAINABILITY

The rapid expansion of food, urban, and industrial systems has led to the generation of billions of tons of solid waste annually. By 2050, global waste is projected to rise from 2.01 billion tons in 2016 to 3.4 billion tons.⁸³ High-income countries, despite comprising only 16% of the global population, contribute 34% of the world's waste. The U.S. Environmental Protection Agency highlights that solid waste landfills are the third-largest source of methane (CH₄) emissions in the U.S., equating to the emissions of 21.6 million passenger vehicles annually.⁸⁴ Open waste burning further exacerbates greenhouse gas emissions, posing significant environmental and public health threats.⁸⁵ Addressing these challenges is more costly than establishing safe waste management systems, necessitating the exploration of alternative, environmentally friendly methods for waste management.

Thermochemical conversion of solid waste into biochar offers a promising solution, aligning with the principles of a circular economy by reducing waste, promoting resource efficiency, and mitigating climate change. Producing biochar from renewable waste sources, such as crop residues, forest residues, and food waste,^{86–89} ensures carbon sequestration and diverts organic matter from landfills. The process involves converting waste through controlled thermochemical processes (300°C to 900°C) into carbon-rich biochar,^{90–91} which addresses both waste disposal and greenhouse gas emissions, particularly CO₂. Various thermochemical methods, including pyrolysis, HTC, microwave-assisted carbonization, and gasification, can be employed.^{92–93} Pyrolysis is favored for biochar production as it retains a substantial portion of feedstock as durable biochar while generating valuable byproducts like bio-oils and gases.⁹⁴ However, high-temperature pyrolysis can release CO₂ and other gases, which can be mitigated by adopting low-temperature or slow pyrolysis techniques and using energy-efficient equipment powered by renewable sources. Innovative methods like microwave-assisted carbonization offer precise heating and reduced emissions.⁹³ Researchers are also exploring biochar production from plastic waste and copyrolysis of organic materials and plastics.^{95–97} Biochar can be produced at various scales, from industrial operations to small household applications, even on farmland.⁹⁸

Beyond waste management, biochar plays a crucial role in circular economy efforts and sustainable development. It captures CO₂⁹⁹ and removes organic and inorganic contaminants from environments.^{100–103} Biochar, when used as a soil amendment, improves soil quality by increasing nutrient retention, enhancing water-holding capacity, boosting agricultural productivity and contributing to carbon sequestration in terrestrial ecosystems.^{104–106} Biochar's multifaceted applications align with sustainable practices and environmental conservation, making it pivotal in achieving carbon neutrality and sustainable development.¹⁰⁷

ENERGY-EFFICIENT CARBONIZATION: MINIMIZING ENVIRONMENTAL FOOTPRINTS

Energy-efficient carbonization processes play a crucial role in reducing carbon emissions and mitigating climate change. Carbonization is the process of converting carbon-containing materials, such as biomass or coal, into carbon-rich products like charcoal or activated carbon while minimizing the release of greenhouse gases. Here are some key strategies and technologies for achieving energy-efficient carbonization and low carbon emissions:

Hydrothermal carbonization (HTC)

HTC is a sustainable process that has gained attention for producing valuable carbonaceous materials by mimicking the natural coalification process

under moderate temperature and pressure.^{108–109} It offers an efficient method for converting high-moisture biomass, rich in cellulose, lignin, and hemicellulose, into carbon-rich materials.²⁸ HTC breaks down complex hydrocarbons into smaller molecules, which then undergo dehydration, decarboxylation, polymerization, and aromatization, forming conjugated aromatic carbon materials,^{110–112} as illustrated in Figure 2K. The process reduces the H/C and O/C ratios,¹¹³ operating at moderate temperatures, thus minimizing CO₂ emissions and eliminating the need for organic solvents or catalysts.¹¹⁴

HTC's mild conditions (180–265°C, up to 6.0 MPa)^{115–116} allow for efficient carbon sequestration and low carbon emissions. The process retains carbon within the hydrochar product, aligning with efforts to mitigate climate change by reducing CO₂ emissions. Unlike traditional carbonization, which requires energy-intensive drying, HTC processes wet biomass directly, enhancing its environmental performance.^{116–119} Chen et al. assessed hydrothermal carbon derived from glucose, lignin, and cellulose, observing that the resulting carbon materials retained spherical morphologies, with larger sizes from lignin and cellulose.¹²⁰ Ru et al. produced modified hydrochar from pomelo peel, demonstrating its effectiveness in mitigating CO₂ emissions.¹²¹ HTC's versatility in feedstock selection, accommodating a wide range of organic materials, further enhances its sustainability by converting waste into valuable products while reducing environmental impact.

Pyrolysis carbonization

Pyrolysis is a thermal process that breaks down organic materials into carbon-rich byproducts at moderate temperatures (300–800°C) under low-pressure, oxygen-deprived conditions.¹²² This method is versatile, sustainable, and capable of low carbon emissions, making it attractive for various applications. During pyrolysis, inert gases like nitrogen or reactive gases like carbon dioxide can maintain anaerobic conditions, preventing complete combustion and significantly reducing greenhouse gas emissions.^{123–125}

Key factors influencing pyrolysis outcomes include the choice of inert gas, gas flow rate, temperature, heating speed, and process duration.¹²⁶ Slow pyrolysis, for example, produces more organized carbon structures, while fast pyrolysis increases structural defects. Liu et al. found that rapid heating of *Arundo donax*-derived PCMs increased defects, as shown by higher I_D/I_G ratios in Raman spectra (Figure 2L).¹²⁷ Yuan et al. reported that slow pyrolysis revealed crystallization, graphitization, and aromatization, and XPS spectra revealed functional group variations depending on the heating rate (Figure 2M).¹²⁸ Pariyar et al. demonstrated that higher pyrolysis temperatures consistently increased the SSA of PCMs derived from various biomass sources, such as pine sawdust and rice husk (Figure 2N).¹²⁹ Yang et al. developed a kinetic model for coal pyrolysis, optimizing conditions to reduce carbon emissions while maximizing high-quality tar production (Figures 2O–P).¹³⁰ Moreover, pyrolysis of lignocellulosic biomass in an inert atmosphere offers the potential for negative carbon emissions, contributing to carbon sequestration.¹³¹ The process yields biochar, syngas, and liquid tar, which can be refined into valuable chemicals and fuels, aligning with low carbon emission strategies and offering a multifaceted approach to combating climate change.¹³²

Laser-induced graphitization

Typically, biomass-derived PCMs are prepared through high-temperature pyrolysis, a slow and energy-intensive process. However, laser-induced graphitization (LIG) has emerged as an efficient alternative, using a laser beam to locally carbonize substrates or precursors, thus minimizing carbon emissions.¹³³ Unlike HTC and conventional pyrolysis, LIG selectively carbonizes specific regions within the precursor, creating electrically conductive graphitic carbon structures.¹³⁴ The basic mechanism of laser-induced graphitization was revealed by Aniruddh et al. and illustrated in Figure 3A.¹³⁵ The CO was detected at the initial stage when the polymer converted into an amorphous structure, while H₂ was evolved steadily as the amorphous structure transformed into an ordered graphitic structure with the 5-, 6- and 7-member carbon rings connecting to form the graphitic carbon network. This innovative approach is particularly relevant in the context of climate change and sustainability, representing a significant advancement in green materials science.

LIG allows precise control over the morphology and electrical properties of

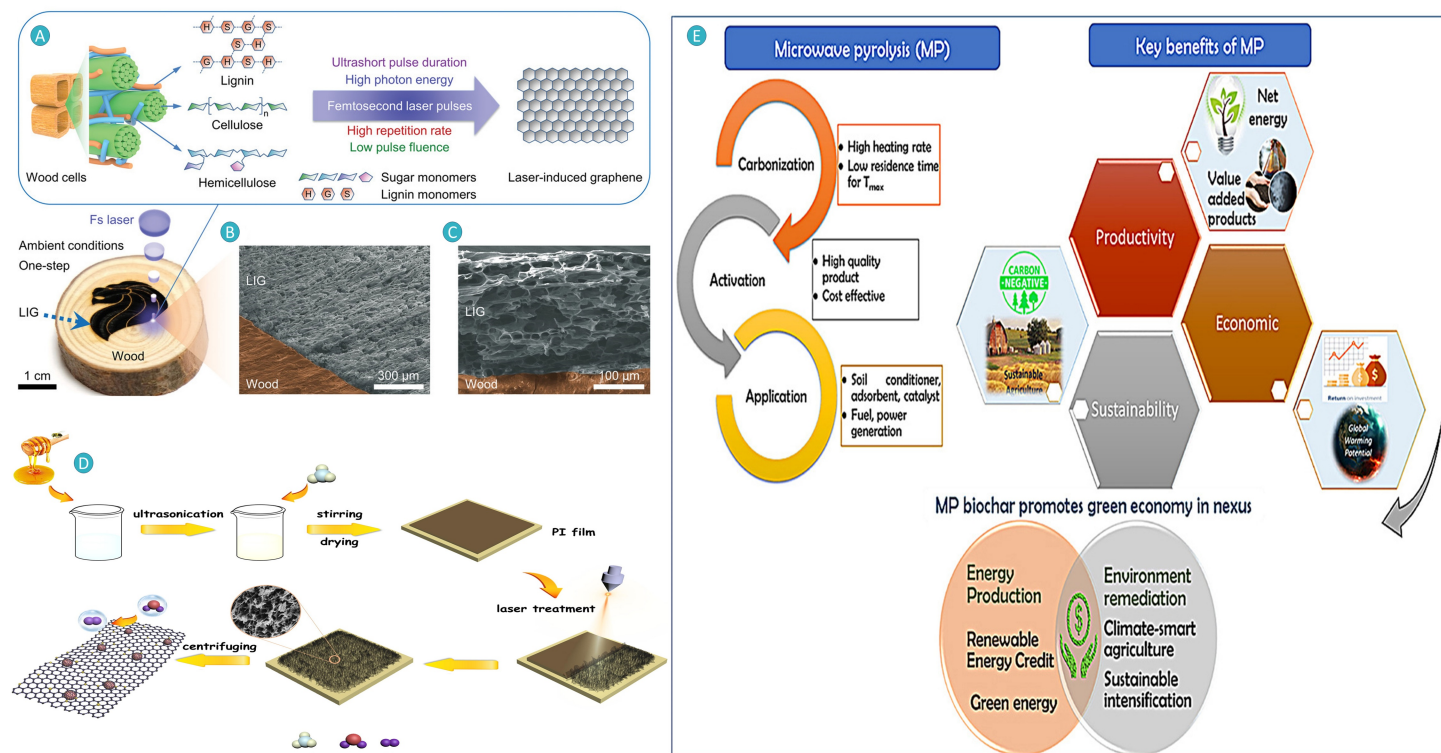


Figure 3. LIG and microwave-assisted pyrolysis of biomass for sustainable PCMs (A) The schematic diagram of LIG.¹³⁵ Copyright 2020, American Chemical Society. (B) Tilted-view and (C) cross-sectional pseudo-color SEM images of LIG on wood.¹³⁸ Copyright 2019, Wiley-VCH. (D) Laser conversion method for synthesizing ruthenium and nitrogen co-doped porous carbon.¹³⁸ Copyright 2021, Elsevier. (E) Overview of microwave-assisted pyrolysis carbon production, addressing environmental and energy challenges.¹⁴¹ Copyright 2021, Elsevier.

carbon-based materials by fine-tuning manufacturing parameters, with laser radiation energy being a crucial factor.¹³⁶ Duy et al. demonstrated that increasing laser energy promotes the formation of graphitic carbon through a dynamic fluid mechanism, transitioning from carbon sheets to fibers and eventually droplets.¹³⁷ This process can utilize various carbon precursors, including polymers, biomass, and waste materials, transforming them into a porous carbon matrix. For example, femtosecond laser direct writing (FsLDW) technology enables the creation of high-quality LIG patterns on wood and leaves under ambient conditions.¹³⁸ The resulting LIG, depicted in Figure 3B and 3C, exhibits a porous, highly graphitic structure. Moreover, the LIG method at room temperature is both simple and rapid, showcasing advantages in terms of energy-saving and high energy utilization efficiency. Additionally, a novel approach using natural honey as a precursor demonstrated the feasibility of rapidly preparing Ru, N co-doped porous carbon at room temperature (Figure 3D).¹³⁸ One of LIG's key advantages is its ability to convert carbon-rich precursors into ordered graphitic structures without the high-temperature treatments that typically produce significant carbon emissions. Traditional carbonization processes require prolonged exposure to high temperatures (1200–3000°C),^{139–140} leading to substantial CO₂ emissions. In contrast, LIG operates at significantly lower temperatures with precision, reducing both energy consumption and emissions.

Microwave-assisted carbonization

Microwave-assisted carbonization (MAC) is an innovative, eco-friendly method for producing carbonaceous materials with low carbon emissions. Using microwave energy within the electromagnetic spectrum (1 mm to 1 m wavelength, 300 MHz to 300 GHz frequency),¹⁴² MAC heats carbon-rich feedstocks like biomass, agricultural residues, and waste materials in a controlled environment. This method operates at lower temperatures and allows rapid, selective heating, significantly reducing carbon emissions compared to conventional methods (Figure 3E).¹⁴¹

MAC offers several advantages: it is highly energy-efficient, with direct microwave absorption leading to internal heating and minimal heat dissipation, thus accelerating reaction kinetics and lowering energy consumption. Additionally, MAC allows precise control over process parameters such as

temperature, pressure, and reaction time, enabling the production of tailored carbon materials for specific applications like adsorption, environmental remediation, and fuel production.^{141,143} Operating in an inert or low-oxygen environment, MAC minimizes CO₂ emissions by preventing feedstock combustion. Furthermore, MAC's versatility extends to various feedstocks, including lignocellulosic biomass, plastics, and organic wastes,¹⁴² making it a promising technology for sustainable carbon material production. When applied to diverse biomass sources, MAC yields biochar, bio-oil, and syngas, offering a sustainable solution across multiple domains, including carbon sequestration and high-performance material development. Studies have demonstrated MAC's efficiency in processing feedstocks like rice husk,³⁴ corn cob,¹⁴⁴ bamboo sawdust,¹⁴⁵ seaweeds,¹⁴⁶ food waste,¹⁴⁷ producing high-quality pyrolytic products with reduced energy input.

Chemical method of carbonization

The synthesis of PCMs from biomass via high-temperature pyrolysis presents challenges, including high energy consumption, the need for inert gases or vacuum to prevent calcination, and significant CO₂ and VOC emissions.¹⁴⁸ To address these issues, more sustainable methods, such as efficient chemical method, are crucial for reducing the environmental impact of PCMs production. Wan et al. successfully synthesized high-surface-area PCMs from cellulose-rich biomass (e.g., filter paper, bamboo waste, and empty fruit bunches) using concentrated sulfuric acid (H₂SO₄) as a dehydration agent, eliminating the need for external heating and reducing emissions.¹⁴⁹ BET analysis showed that this method produced carbon with superior surface properties compared to traditional carbonization. Additionally, a novel, environmentally friendly approach was used to modify kaolin clay with carbon for electrochemical detection of quercetin, resulting in an electrode with enhanced catalytic activity and no carbon emissions.¹⁵⁰

In solar steam generation (SSG) applications, traditional carbonization of plant materials is energy-intensive and environmentally harmful. To overcome this, Xiaoli Shan and colleagues developed a concentrated acid-induced dehydration method to transform fallen leaves into carbon powders, termed "fallen-leaf photothermal film prepared by dehydration" (FLPD).¹⁵¹ The effectiveness of this method in producing porous carbon structures, high-

Table 3. The comparison of CO₂ adsorption efficiency between green activation and traditional activation strategies.

Activation strategy		Porosity		CO ₂ adsorption efficiency [mmol g ⁻¹]	Environmental risks	Reference
		S _{BET} [m ² g ⁻¹]	Pore volume [cm ³ g ⁻¹]			
Green activator		1000~3000	0.9~2.0	1.6~4.13	Environmentally friendly	195-197
Steam activation		500~1000	0.2~0.8	0.73~3.77	Environmentally friendly	197,197~198,198
Self-activation	Green activation	500~2500	0.2~2.3	2.3~4.11	Environmentally friendly	197,199~200
Green template		180~580	0.13~0.24	1.2~2.39	Environmentally friendly	201-203
KOH		500-3000	0.2~1.2	4.05~9.09	Environmentally harmful	204-206
ZnCl ₂	Traditional activator	200-2000	0.1~1.2	0.85~4.81	Environmentally harmful	204,207~208

lighting dehydration or chemical as a sustainable alternative for creating carbon materials with nearly zero emissions.

GREEN ACTIVATION AGENTS AND TEMPLATES: A SUSTAINABLE APPROACH TO PCMs MODIFICATION

PCMs have been extensively applied in various fields, including energy storage systems, gas adsorption, catalyst supports, and more. From a purely academic point of view, the preparation of PCMs typically involves the use of highly corrosive agents (such as KOH, ZnCl₂, NaOH, etc.), which can induce intense redox reactions with carbon precursors, consequently leading to significant carbon emissions. However, from an industrial perspective, most commercially used porous carbon materials are produced through the physical pyrolysis of biomass wastes using steam as an activator. This preference arises due to the instability and high cost of laboratory-grade precursors, as well as the hazards associated with corrosive chemical activators. Considering safety and the potential for large-scale production, researchers have increasingly turned their attention to emerging green activation strategies. Green activation involves replacing harsh chemical activators with more environmentally friendly alternatives and leveraging the self-activation of inorganic substances that naturally form during the carbonization process. This approach also minimizes chemical damage to production equipment. Furthermore, a detailed comparison of the characteristics of porous carbon materials synthesized via green activation and traditional activation methods is summarized in Table 3, providing a comprehensive understanding of these emerging activation strategies.

Chemical green activation agents

After implementing carbon emission controls during carbonization, enhancing the porosity of carbon materials becomes crucial for optimizing their performance in various applications.¹⁵²⁻¹⁵⁴ Activation is a key process in which gases or chemical agents create micropores, mesopores, and macropores in carbon materials.¹⁵⁵ However, the use of environmentally friendly activation agents is essential to minimize carbon emissions. Traditional chemical activation methods employ harsh agents such as KOH, NaOH, ZnCl₂, or H₃PO₄, which are highly corrosive and environmentally harmful.¹⁵⁵ Among these, KOH and ZnCl₂ are categorized as "Extremely Hazardous" (Figure 4A).¹⁵⁴ Recent research has focused on more eco-friendly activation strategies, such as using potassium carbonate (K₂CO₃), a milder and less toxic alternative to KOH. K₂CO₃ acts as a porogenic, creating pores through redox reactions with carbon.¹⁵⁶⁻¹⁵⁷ At temperatures above 850°C, K₂CO₃ decomposes, facilitating the ongoing activation process by generating CO₂, which reacts with carbon to form new pores.¹⁵⁸ Additionally, K₂CO₃ preserves the precursor's morphology and enhances carbon yield by promoting the carbonization of biomass, offering a catalytic effect similar to more toxic agents like ZnCl₂ and H₃PO₄.^{157,159} Greener activation agents such as KHCO₃, K₂C₂O₄, CH₃CO₂K, K₂SO₄, Na₂S₂O₃, Na₂CO₃, NaHCO₃, Na₂SO₄, and Na₂S₂O₅, provide environmentally friendly alternatives for PCMs synthesis (Figure 4B).¹⁵⁴ These agents not only minimize environmental impact but also enhance the adsorption capabilities of PCMs, paving the way for more sustainable and innovative approaches in PCMs production.

Physical green activation agents

While chemical activation can enhance PCMs performance, it is crucial to develop green and sustainable methods, especially since chemical activation is typically limited to laboratory-scale production. In response to environmental challenges, physical activation using green agents like water vapor (steam) and CO₂ has emerged as a sustainable alternative. These methods produce high-quality carbon materials with significantly reduced carbon emissions and align with sustainability goals.¹⁶⁰

Steam activation, a mild process compared to KOH, involves exposing carbon materials to steam at high temperatures, promoting pore formation without harmful byproducts. This method enhances porosity through mechanisms such as tar elimination, micropores generation, and pore expansion, influenced by parameters like temperature and reaction time. For instance, steam-activated cellulose fibers demonstrated remarkable CO₂ adsorption due to their microporous structure (Figure 4C),¹⁶¹ and steam-activated biochar from pine sawdust showed improved textural characteristics (Figure 4D).¹⁶²

CO₂ activation, conducted during or after pyrolysis, involves the Boudouard reaction, which enhances porosity and surface area without additional CO₂ emissions. CO₂ activation is particularly appealing as it can utilize CO₂ from industrial emissions, supporting carbon capture and utilization (CCU). For example, Lee et al. produced porous carbon fibers with specific surface areas up to 1012 m²/g using CO₂ activation,¹⁶³ while Kozyatnyk et al. observed varied porosity in biochars activated with CO₂, depending on the precursor and conditions.¹⁶⁴ Additionally, CO₂ activation of waste packing peanuts produced highly porous carbon microspheres for CO₂ capture, recycling the gas and aligning with sustainability principles (Figure 4E).¹⁶⁵

Self-activation agents

The self-activation technique offers a sustainable and cost-effective method for producing porous carbons without external activating agents, utilizing substances inherent in the carbon precursor, particularly biomass. This method involves two main routes: physical self-activation, where reactive gases like CO₂ and H₂O generated during pyrolysis interact with the carbonaceous material,¹⁷⁰⁻¹⁷¹ and chemical self-activation, which leverages alkali elements like potassium (K) and sodium (Na) naturally present in biomass to form porous structures (Figure 4F).¹⁷²⁻¹⁷³ These processes can sometimes operate simultaneously, potentially enhancing porosity.

Physical self-activation relies on gasification reactions, requiring controlled pyrolysis conditions to favor pore development. For example, Bommier et al. increased the BET surface area of PCMs by restricting argon flow during cellulose pyrolysis.¹⁷⁴ Another method involves carbonization in a closed reactor without carrier gas, leading to high surface areas and pore volumes.¹⁷⁵ Doped carbons, such as N, O-doped porous carbons, can also be produced using this approach, as demonstrated by Yang et al. with hollyhock leaves.¹⁷⁰

Chemical self-activation uses the inherent alkali elements in biomass, which form carbonates (K₂CO₃, Na₂CO₃) during pyrolysis, acting as activating agents to create porous structures. Inorganic compounds like calcium and magnesium carbonates also contribute to pore formation. Inagaki et al. showed that kenaf inner cores with a high potassium content produced PCMs with a surface area of 1400 m²/g.¹⁷⁶ Other biomass sources, such as

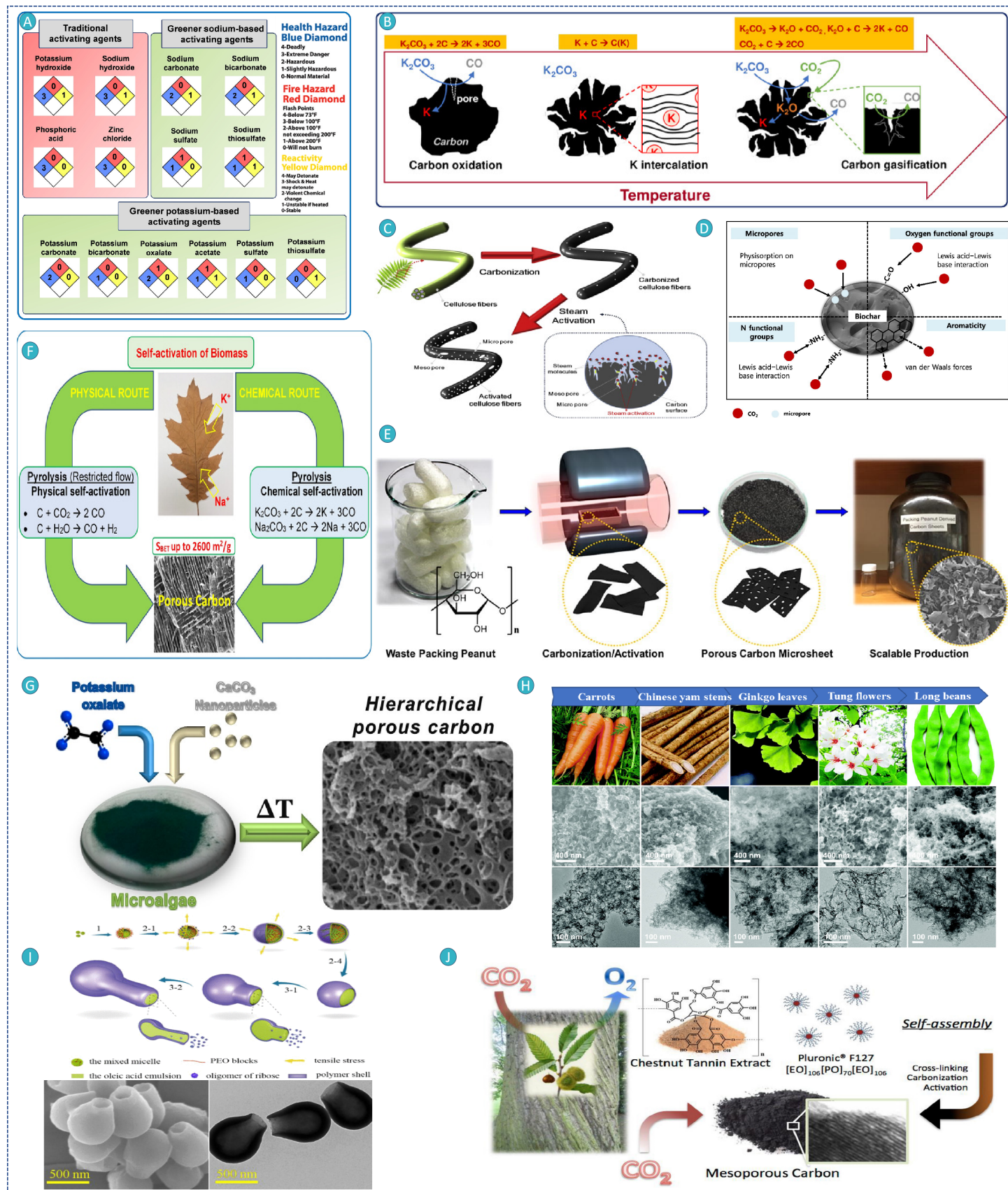


Figure 4. Sustainable modification of PCMs using green activation agents and templates (A) Labels of traditional and greener chemical activating agents. (B) Pore generation mechanism with K_2CO_3 .¹⁵⁴ Copyright 2021, Wiley-VCH. (C) Preparation of porous carbons and steam activation of the surface.¹⁶¹ Copyright 2015, Elsevier. (D) Biochar with increased microporosity, surface area, and oxygen-containing functional groups after steam activation.¹⁶² Copyright 2020, Elsevier. (E) Porous carbon microspheres from waste packing peanuts via carbonization, physical, and chemical activation.¹⁶⁵ Copyright 2020, Elsevier. (F) Schematic of physical and chemical self-activation of biomass during carbonization.¹⁵⁴ Copyright 2021, Wiley-VCH. (G) Sustainable one-pot synthesis of hierarchical porous carbons from microalgae biomass.¹⁶⁶ Copyright 2017, American Chemical Society. (H) Hierarchically porous heteroatom-doped carbons from five biomass precursors, showing similar structures in FESEM and TEM images.¹⁶⁷ Copyright 2019, Royal Society of Chemistry. (I) Formation of HOCFs using a hydrothermal method, confirmed by SEM and TEM.¹⁶⁸ Copyright 2017, American Chemical Society. (J) Mesoporous carbon created through soft templating using chestnut tannin as a carbon precursor.¹⁶⁹ Copyright 2016, Elsevier.

seaweeds rich in potassium-rich carbohydrates like carrageenan and sodium alginate, have also yielded high surface areas.¹⁷⁷ Zhang et al. found that lotus stems, with higher K and Na content, produced porous carbon with a surface area of 1610 m²/g, compared to the lower surface area from leaves.¹⁷² He et al. produced N-doped porous carbons with a surface area of up to 1190 m²/g using nitrogen-rich biomass like celery plants, showcasing the potential of self-activation for producing functional materials suitable for applications like CO₂ adsorption.¹⁷⁸

Green template method

Unlike the self-activation strategy that solely relies on intrinsically self-generated inorganic salt templates or physical gases from carbon precursors without the addition of external activators, the green templating method involves the use of additional inherent inorganic and organic templates. A detailed discussion of this environmentally friendly pore-forming method is provided below.

Creating PCMs through green template methods while minimizing carbon emissions is a significant advancement in sustainable material science. Template methods involve using sacrificial templates, like organic or inorganic materials, to create well-defined porous structures in carbon materials.^{36,179} Hard templating is a common approach using rigid templates like mesoporous silica, zeolites, MgO and Al₂O₃ to form specific pore structures in carbon materials.^{180–187} Among the various oxide templates, silica stands out as one of the most well-established choices for mesoporous carbon synthesis, and certain silica templates are available in commercial production.^{181,188} Although effective, this method can be hazardous, complex, and costly. To make it more sustainable, researchers developed a one-pot process using biomass-derived products and calcium carbonate nanoparticles as templates. This method creates hierarchical porous carbons with large surface areas and pore volumes, easily removing inorganic residues with a simple acid wash (Figure 4G).¹⁶⁶ Additionally, biomass precursors such as shrimp skin and various other biomass sources, offering versatility for scalable production (Figure 4H).^{167,189} The hard template method has also enabled the synthesis of single-atom metal-nitrogen/phosphorus/sulfur-carbon catalysts, such as graphitic phosphorus-coordinated single-atom Fe catalysts, demonstrating potential for hydrogenative transformations.¹⁹⁰

In contrast, the soft templating approach is greener and more efficient, using organic molecules like surfactants or polymers to self-assemble into micelles that create porous carbon during carbonization.^{191–194} This method allows for intricate porous structures and can be tailored for specific properties. For example, hollow open carbon nanoflakes were synthesized using P123 and sodium oleate micelles with ribose (Figure 4I),¹⁶⁸ and mesoporous carbons from chestnut tannin were produced using Pluronic F127 as a soft template, facilitated by gallic acid (Figure 4J).¹⁶⁹ Integrating low-carbon practices into these methods involves selecting environmentally friendly surfactants and copolymers and optimizing energy-efficient processes for template removal. This approach promotes resource efficiency, lowers energy consumption, and utilizes sustainable precursors, contributing to a reduced carbon footprint in PCMs production.

DISCUSSIONS ON THE DIFFERENCES BETWEEN EMERGING AND TRADITIONAL ACTIVATION TECHNOLOGIES

PCMs reported in previous studies are typically prepared using traditional chemical activation methods involving carbonization and highly corrosive activators such as KOH, ZnCl₂, NaOH, and H₃PO₄. These processes not only release toxic gases at high temperatures but are also time-consuming and costly. To address these issues, two primary strategies have been developed: the use of efficient green activators and the implementation of emerging carbonization technologies. Green activator strategies focus on replacing conventional chemical agents with environmentally friendly alternatives, including green activation agents, self-activation agents, and green templates. Compared to traditional chemical activation methods, green activators facilitate milder redox reactions by combining physical and chemical activation through the inherent decomposition of the green agents (e.g., $2\text{KHCO}_3 \rightarrow \text{K}_2\text{O} + \text{CO}_2 + \text{H}_2\text{O}$). This approach enhances the operational simplicity of the experiments while maintaining effective pore-etching capability. Self-activation refers to the use of self-generated activators from

carbon precursors without the addition of external pore-forming agents, effectively achieving a 'two birds with one stone' approach. Notably, carboxymethyl cellulose,^{209–210} glycolates,²¹¹ biomass-based organic salts²¹² are typical examples of self-generated activator carbon materials.

The green template method, which combines both hard and soft templates, involves using sacrificial templates such as organic or inorganic materials to create well-defined porous structures in carbon materials. This methodology allows for precise tuning of the pore structure of PCMs at the micrometer scale, while also enabling the creation of ordered structures with superior capacitive and adsorption characteristics.²¹³ The emerging carbonization technologies mainly include laser-induced graphitization and microwave-assisted carbonization. In laser-induced graphitization, graphitic conductive carbon materials are directly prepared by scanning a laser beam. It has been reported that the graphitization structure can be selectively realized at low temperatures without carbon emissions, in contrast to traditional carbonization. When the laser focuses on carbon-rich precursors, the inherent atomic structure of the polymers is disrupted due to the increased temperature from the concentrated laser, causing the carbon atoms to reorganize into 5 and 7 membered carbon rings, thereby resulting in conductive graphitic carbon materials.²¹⁴ Another emerging efficient and environmentally friendly strategy is microwave-assisted carbonization, which generates heat as weak molecular bonds break down and new ones form, originating from the changes in molecular motion induced by the adsorption of microwaves.²¹⁵ Unlike conventional carbonization, microwave-assisted carbonization utilizes the inherently generated heat to induce material heating from within, rather than from the surface, enabling faster thermal treatment and reducing carbon emissions.

LIFE CYCLE ASSESSMENT: A HOLISTIC EVALUATION OF SUSTAINABILITY

Life cycle assessment (LCA) of PCMs with low carbon emissions evaluates their environmental impact from raw material extraction through production, use, and disposal. The goal is to quantify and minimize carbon emissions to ensure sustainability. As the use of PCMs grows LCA is crucial for assessing their environmental footprint.^{216–217} Alternative raw materials, like biomass-based agricultural and industrial residuals, offer potential to reduce emissions, but their effectiveness varies.³⁸ Choosing appropriate biomass feedstocks and optimizing transportation are essential for minimizing the carbon footprint of activated carbon production. A cradle-to-gate LCA of activated carbon, including sources like coal, wood, and coconut shells, reveals that coal-based granular activated carbon (GAC) has the highest environmental impact, while GAC from coconut, wood, and reactivated coal shows lower impacts (Figure 5A).²¹⁶ Reactivated GAC had the lowest global warming potential (GWP) when biogenic emissions were included, while excluding them lowered GWP for coconut and wood GAC (Figure 5B). Transparent reporting of both biogenic and non-biogenic emissions is crucial.

Recent studies focus on using local waste materials as feedstocks for activated carbon production.^{218–219} Comparative LCA of various waste-derived activated carbons provide insights into their environmental footprint.^{220–221} Zhu et al. LCA of biochar production from agro-residues highlighted its carbon sequestration potential and versatility (Figure 5C).²²² Biochar's production design should align with local contexts to maximize benefits. An LCA of seaweed, microalgae, and lignocellulosic biomass for biochar-derived carbon-catalysts revealed that KOH activation had the highest environmental burdens (Figures 5D–G).²²³ Noemi et al. assessed the impact of activated carbon from coconut shells in Indonesia, finding that transitioning to renewable energy could significantly reduce environmental impacts.²²⁴ Comparisons between graphene and activated carbon showed that, currently, graphene-based PCMs have higher environmental impacts, though future improvements could make them more sustainable.²²⁵ Overall, LCA is crucial for optimizing each phase of PCMs production to minimize carbon emissions and enhance sustainability.

CARBON CAPTURE STORAGE AND UTILIZATION

The rising atmospheric CO₂ levels, which reached 421 ppm in 2022 from around 280 ppm pre-industrially, primarily result from industrial activities

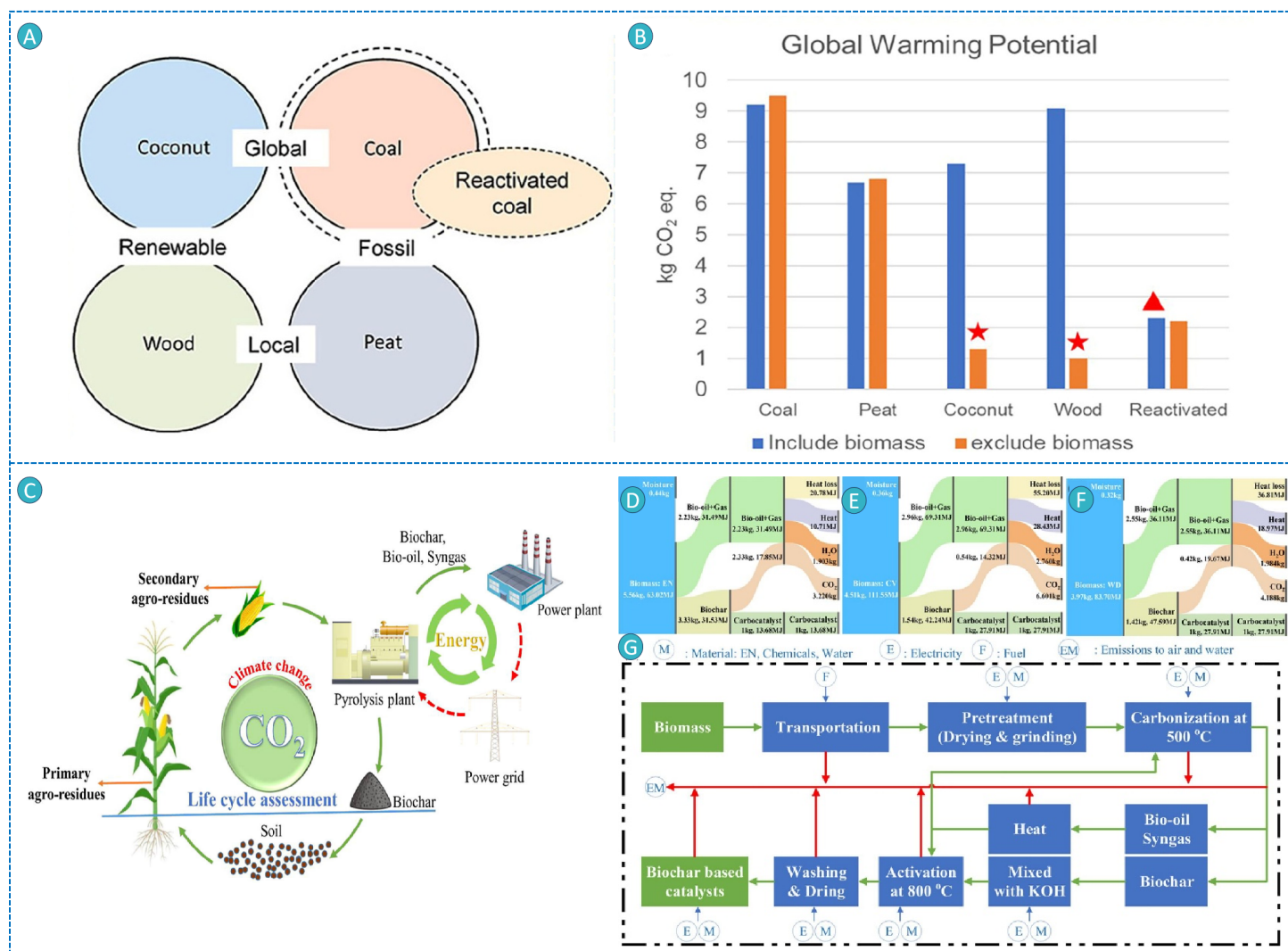


Figure 5. LCA of biomass-derived carbons for sustainable production and carbon neutrality (A) Cradle-to-gate LCA comparing the GWP of carbon precursors: coal, coconut shell, wood, peat, and reactivated coal-activated carbons. (B) GWP comparison of including and excluding biogenic carbon emissions.²¹⁶ Copyright 2022, Elsevier, under CC BY license. (C) LCA for biochar production from agro-residues via pyrolysis for carbon neutrality in a circular economy.²²² Copyright 2022, Elsevier. (D, E, F) Analysis of material and energy flows during BDC production from seaweed, microalgae, and lignocelluloses. (G) System boundaries and input/output processes for producing 1 kg of BDCs.²²³ Copyright 2022, Elsevier.

since the 1800s.²²⁶ This increase poses severe climate challenges. Carbon capture storage and utilization (CCSU) techniques address climate change by capturing CO₂ from industrial processes and repurposing it, offering a practical alternative to traditional carbon capture and storage (CCS).^{227–228} CCSU promotes CO₂ recycling and is gaining global traction for reducing emissions and supporting economic growth. In large-scale porous carbon production, integrating CCSU starts with capturing CO₂ emissions at their source. This prevents CO₂ from entering the atmosphere, mitigating the carbon footprint and enhancing sustainability. CO₂ capture methods include pre-combustion, post-combustion, and oxy-fuel combustion.²²⁹ Post-combustion capture is widely adopted due to its efficiency and CO₂ selectivity, using methods like chemical absorption, adsorption, membrane separation, cryogenics, hydrate formation, and microbial approaches.²³⁰

Adsorption using solid-phase porous materials is an effective CCSU method, leveraging forces between adsorbents and CO₂ for selective separation. Activated carbon, with its high surface area (500 to 1700 m²/g) and microporous structure, is a prominent adsorbent due to its strong adsorption capacity, cost-effectiveness, and ease of regeneration.^{231–232} Research continues to improve its adsorption capabilities, reinforcing its role in CO₂ capture while outlining various carbon storage and utilization technologies.²³³

APPLICATIONS OF PCMs IN MITIGATING CO₂

Chemical-modified PCMs for CO₂ capture

PCMs derived from sustainable biomass through chemical activation at elevated temperatures are highly effective for CO₂ capture, featuring enduring porosity, significant surface area, and adaptable morphology.¹²² Sevilla et al. advanced PCMs using HTC and KOH activation, achieving a BET surface area of 2850 m² g⁻¹ and CO₂ capture capacities of 5.2–5.8 mmol g⁻¹ at 1 bar, 0°C, and 2.9–3.5 mmol g⁻¹ at 1 bar, 25°C.^{234–235} Singh et al. developed PCMs from *Arundo donax* biomass, with KOH-ZnCl₂-activated PCMs showing a CO₂ uptake of 30.2 mmol g⁻¹ at 30 bar, 0°C, the highest reported among biomass-derived carbons (Figures 6A–C).^{236–238} Serafini et al. prepared microporous carbons from walnut shell biomass, exhibiting a surface area of 1868 m² g⁻¹ and CO₂ adsorption capacities of 9.54 mmol g⁻¹ at 0°C, 5.17 mmol g⁻¹ at 25°C, and 4.33 mmol g⁻¹ at 40°C under 1 bar.²³⁹ Vazhayal et al. created nitrogen-rich PCMs from aquatic plants, achieving CO₂ capture of 6.01 mmol g⁻¹ at 0°C, 1 bar (Figures 6D–F).²⁴⁰ Wang et al. synthesized PCMs with a BET surface area of 1903 m² g⁻¹ and a CO₂ uptake of 5.41 mmol g⁻¹ at 0°C and 3.66 mmol g⁻¹ at 25°C.²⁴¹ Song et al. used soybean cake biomass to create nanoporous carbons, yielding a BET area of 1712 m² g⁻¹ and CO₂ adsorption of 4.19 mmol g⁻¹ at 0°C and 6.61 mmol g⁻¹ at 25°C under 1 bar.²⁴² Li et al. synthesized PCMs from tobacco and urea-based biochar, showing high CO₂

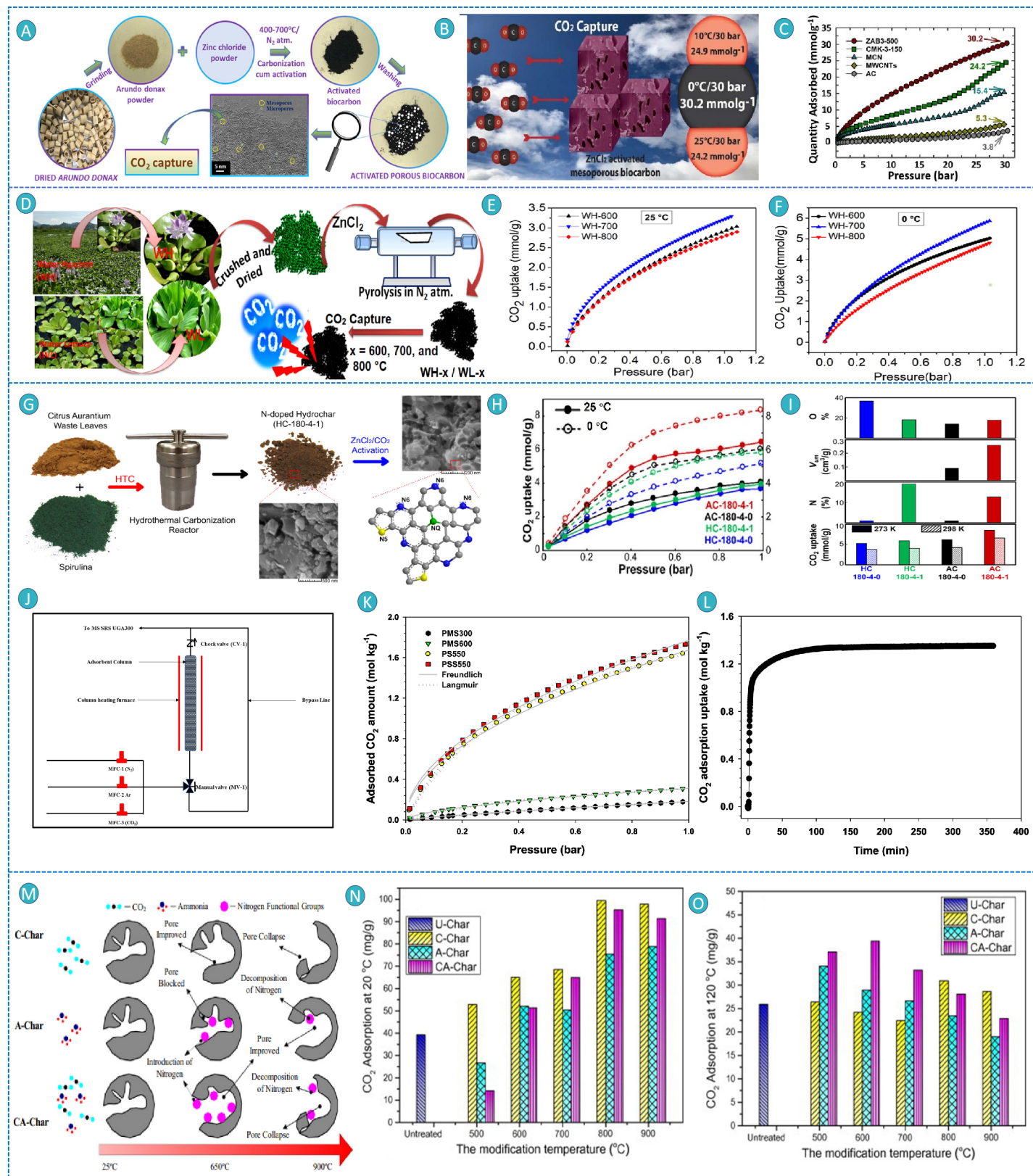


Figure 6. PCMs for enhanced CO₂ adsorption and capture (A) Schematic of activated bio-carbon synthesis. (B) Mesoporous-activated bio-carbons (ZnCl₂ activated) show a CO₂ adsorption capacity of 30.2 mmol g⁻¹ at 0°C/30 bar. (C) Comparison of CO₂ uptake between biomass and non-biomass carbons.²³⁶ Copyright 2017, American Chemical Society, Copyright 2017. (D) Sustainable nitrogen-doped nanoporous carbon production from aquatic weeds (water hyacinth and water lettuce). (E, F) CO₂ adsorption capacity of water hyacinth at 25°C and 0°C.²⁴⁰ Copyright 2022, Elsevier. (G) Co-hydrothermal carbonization of C. aurantium waste and Spirulina to produce N-doped hydrochar. (H) CO₂ adsorption at 273 and 298 K for optimized carbon samples. (I) Nitrogen content, ultra-micropore volume, and oxygen content on CO₂ uptake.²⁴⁴ Copyright 2020, American Chemical Society. (J) Schematic for CO₂-N₂ dynamic breakthrough experiments. (K) CO₂ adsorption isotherms of pine sawdust and paper mill sludge biochars at 25°C. (L) CO₂ adsorption kinetics of PS550 at 30°C.¹⁶² Copyright 2020, Elsevier. (M) Nitrogen enriched biochar modified by high temperature CO₂-ammonia treatment. CO₂ adsorption capacities of various biochars at (N) 20°C and (O) 120°C.²⁵⁸ Copyright 2014, Elsevier.

absorption under pressures of 30–40 bar.²⁴³ Priye et al. used Citrus aurantium leaves and microalgae for nitrogen-doped activated carbon, achieving a CO₂ capture of 8.43 mmol g⁻¹ at 0°C and 1 bar, with high selectivity and quick adsorption kinetics (Figures 6G–L).²⁴⁴

Biochar, derived from natural biomass or agricultural waste, is a cost-effective and eco-friendly CO₂ adsorbent. Although pristine biochar has limited CO₂ adsorption capacity, modifications have greatly improved its effectiveness.²⁴⁴ Singh et al. synthesized nanoporous activated bio-carbons (NABs) from alligator weed (AW) using KOH impregnation and carbonization at 800°C, resulting in NABs with a high surface area (3106 m² g⁻¹), large pore volume (1.62 cm³ g⁻¹), and tunable microporosity. These NABs showed superior CO₂ adsorption, capturing 30.4 mmol g⁻¹ at 0°C and 23.3 mmol g⁻¹ at 25°C under high pressure (30 bar).²⁴⁵ Another study converted grape marc into porous activated bio-carbons (PABs) with a specific surface area of 2473 m² g⁻¹ and remarkable CO₂ capture, achieving 6.2 mmol g⁻¹ at 0°C/1 bar and 26.8 mmol g⁻¹ at 0°C/30 bar.²⁴⁶ Coskun et al. synthesized microporous nitrogenated carbon (MCN) with a nitrogen content of 13.3% and a BET surface area of 1730 m² g⁻¹, demonstrating excellent CO₂/N₂ selectivity and CO₂ adsorption capacity.²⁴⁷

Salts like ZnCl₂ are commonly used to activate carbon materials due to their strong dewaterability, which facilitates micropore development during pyrolysis. Vargas et al. utilized ZnCl₂ to produce CO₂ sorbents from palm stones, achieving a CO₂ absorption capacity of 3.8 mmol g⁻¹ at 0°C and 1 bar due to abundant microporosity.²⁴⁸ Zhang et al. created hierarchically porous carbons (HPCs) from cork dust using a two-step ZnCl₂ activation process, resulting in high CO₂ adsorption capacities of 4.64 mmol g⁻¹ at 0°C and 2.75 mmol g⁻¹ at 25°C, with a BET surface area of 1853 m² g⁻¹ and a micropore volume of 0.839 cm³ g⁻¹.²⁴⁹ Other activating agents like NaOH, H₃PO₄, and K₂CO₃ have also been explored for creating micropores in carbon structures.²⁵⁰

Introducing heteroatoms, especially nitrogen, into carbon materials enhances CO₂ uptake by increasing surface alkalinity. Nitrogen doping, which modifies pore structure and adds N-containing groups, is particularly effective.³¹ Wei et al. synthesized N-doped PCMs from anthracite using ball milling and urea treatment, resulting in a high BET surface area (1615 m² g⁻¹) and a CO₂ uptake of 4.46 mmol g⁻¹ at 1 bar and 25°C.²⁵¹ Researchers also created N-doped porous carbons from coconut shells, showing CO₂ uptake over 7 mmol g⁻¹ at 0°C and 1 bar.²⁵² Chen et al. used crab shells to produce activated carbons with a CO₂ adsorption capacity of 4.37 mmol g⁻¹ at 1 bar and 25°C.²⁵³ To reduce costs, nitrogen-rich biomass like microalgae is suggested.²⁵⁴ Additionally, sulfur doping or co-doping with multiple atoms can further enhance CO₂ adsorption. Seema et al. synthesized S-doped porous carbon with a CO₂ uptake of 4.5 mmol g⁻¹, higher than nitrogen-doped materials.²⁵⁵ Guo et al. combined N, S, and O in activated carbon from poplar sawdust, achieving a CO₂ uptake of 5.61 mmol g⁻¹ at 0°C.²⁵⁶

Physical-modified PCMs for CO₂ capture

Activating chemicals like KOH and ZnCl₂, while effective for creating porous carbons, pose environmental risks due to their toxic and corrosive nature, contributing to greenhouse gas emissions and ecological harm.¹⁵⁴ To mitigate these issues, researchers are exploring green activation methods, such as physical activation using steam, air, or CO₂, which offer a more sustainable approach. These methods aim to achieve high CO₂ adsorption capacities in carbon materials without harmful waste, aligning with sustainability goals for carbon capture technology with minimal environmental impact.

Steam activation of carbon materials enhances their structure by creating new pores and expanding existing ones, leading to improved CO₂ uptake. For example, Young-Jung et al. used cellulose fibers and found that steam activation significantly increased CO₂ adsorption capacity (3.78 mmol g⁻¹) due to the development of a microporous structure.¹⁶¹ Igalavithana et al. showed that steam activation of pine sawdust produces biochar with a high surface area, abundant micropores, and high aromaticity. These features, along with oxygen-containing basic functional groups, enhance CO₂ adsorption through van der Waals and polar interactions, making pine sawdust-derived biochar a strong candidate for CO₂ capture (Figures 6J–L).¹⁶²

CO₂ activation significantly enhances the porosity and surface area of carbon materials. Lee et al. demonstrated that CO₂ activation can produce porous carbon fibers with a specific surface area of up to 1012 m² g⁻¹,

primarily composed of micropores.¹⁶³ For instance, Soybean straw biochar, modified through CO₂ activation, NH₃ ammonification, and combined CO₂-NH₃ treatment, achieved a high CO₂ adsorption capacity, with the CO₂-NH₃ modification showing the best performance at 88.89 mg g⁻¹.²⁵⁷ Additionally, combining high-temperature ammonia treatment with CO₂ activation for cotton stalk biochar significantly improved CO₂ adsorption, peaking at 99.42 mg g⁻¹ at 800°C (Figures 6M–O).²⁵⁸ Various other modification methods, including metal impregnation and plasma modification, are also being explored to further enhance carbon materials.³¹

PCMs for electrochemical reduction of CO₂

Electrochemical CO₂ reduction reaction (CO₂RR) is gaining interest for converting CO₂ into valuable chemicals using renewable electricity, contributing to carbon neutrality and energy storage.²⁵⁹ Despite achieving industrial-level current densities, the stability of catalysts remains a challenge due to surface reduction, intermediate poisoning, and active component aggregation during CO₂RR.²⁶⁰ Carbon materials, particularly those derived from biomass, offer advantages such as stability, developed pore structures, and low cost. However, they often lack active components necessary for efficient CO₂ activation. To enhance CO₂RR performance, researchers have focused on incorporating defects, heteroatoms, and metal elements into carbon materials. For example, nitrogen (N) doping has been shown to create defects that act as active sites for CO₂ conversion, achieving a CO Faradaic efficiency (FE) of 80%.²⁶¹ Zhang et al. used biomass-derived carbon aerogels doped with nitrogen from melamine, resulting in a BET surface area of 1038.2 m²/g and a CO₂ FE of 75.9% (Figures 7A–B).^{262–263} Carbon catalysts from algae biomass, produced through a thermochemical approach, reached a maximum CO FE of 97.6% at -0.55 V vs RHE (Figures 7C–D).²⁶⁴ A nitrogen-doped nanoporous carbon sheet from *Typha* biomass achieved 90% CO selectivity at a low overpotential of -0.31 V,²⁶⁵ while a nitrogen-doped PCM from wheat flour showed an FE of 83.7% with high activity and durability.²⁶⁶ A 3D N-doped graphitized carbon material from cedar biomass exhibited a CO FE of 91% at 0.56 V (Figures 7E–F).²⁶⁷ Chen et al. developed N, P-co-doped carbon aerogels with a maximum CO FE of 99.1% and a partial current density of -143.6 mA cm⁻².²⁶⁸ To achieve carbon neutrality, further research into the formation mechanisms of biomass-derived carbon materials, along with experimental and simulation analyses of CO₂ adsorption and CO₂RR, is essential. Developing scalable technologies for large-scale production is also recommended to meet practical implementation needs.

Carbon-enhanced biochar soil for sequestration

Rising atmospheric CO₂ levels and significant soil carbon loss pose a threat to global food security and human health. Biochar, a high-carbon material produced by pyrolyzing biomass, has emerged as a sustainable solution for carbon sequestration in soil.²⁶⁹ Its unique properties enhance soil water retention, nutrient holding, and fertility, while its porous structure supports microbial activity, improving soil health and long-term carbon storage. Biochar's high carbon content and refractory nature allow it to efficiently sequester carbon, reducing atmospheric CO₂ levels.^{270–272} Key factors such as biochar particle size, surface area, porosity, and pore size distribution are critical for maximizing carbon sequestration.²⁷³ Smaller biochar particles, like those from *Camellia oleifera* fruit shells (0.5–2 mm), have been shown to lower CO₂ and N₂O emissions and offer more surface area for carbon adsorption.^{274–275} Biochar's porous structure also supports microbial colonization, which further enhances long-term carbon sequestration by stabilizing organic carbon compounds.^{276–277}

Biochar's complex effects on soil carbon sequestration involve several mechanisms that increase soil organic carbon (SOC) storage (Figure 7G).²⁶⁹ A four-year field trial in northern China demonstrated that biochar increased SOC sequestration rates by 31.8% to 47.8%, although it also increased SOC variability. Optimal biochar addition rates were recommended at 1.8 to 3.6 tons per hectare per year for the North China Plain.^{278–279} Additionally, biochar protects labile organic carbon from microbial degradation, slowing carbon mineralization and leading to SOC accumulation.²⁷¹ A decade-long field study showed an 18% reduction in native SOC mineralization due to biochar's protective effects.²⁸⁰ Globally, biochar could sequester about 5.5 petagrams (Pg) of CO₂ annually, contributing to 25% of potential CO₂ removal through better land management.²⁸⁶ Biochar's role in sustainable land management

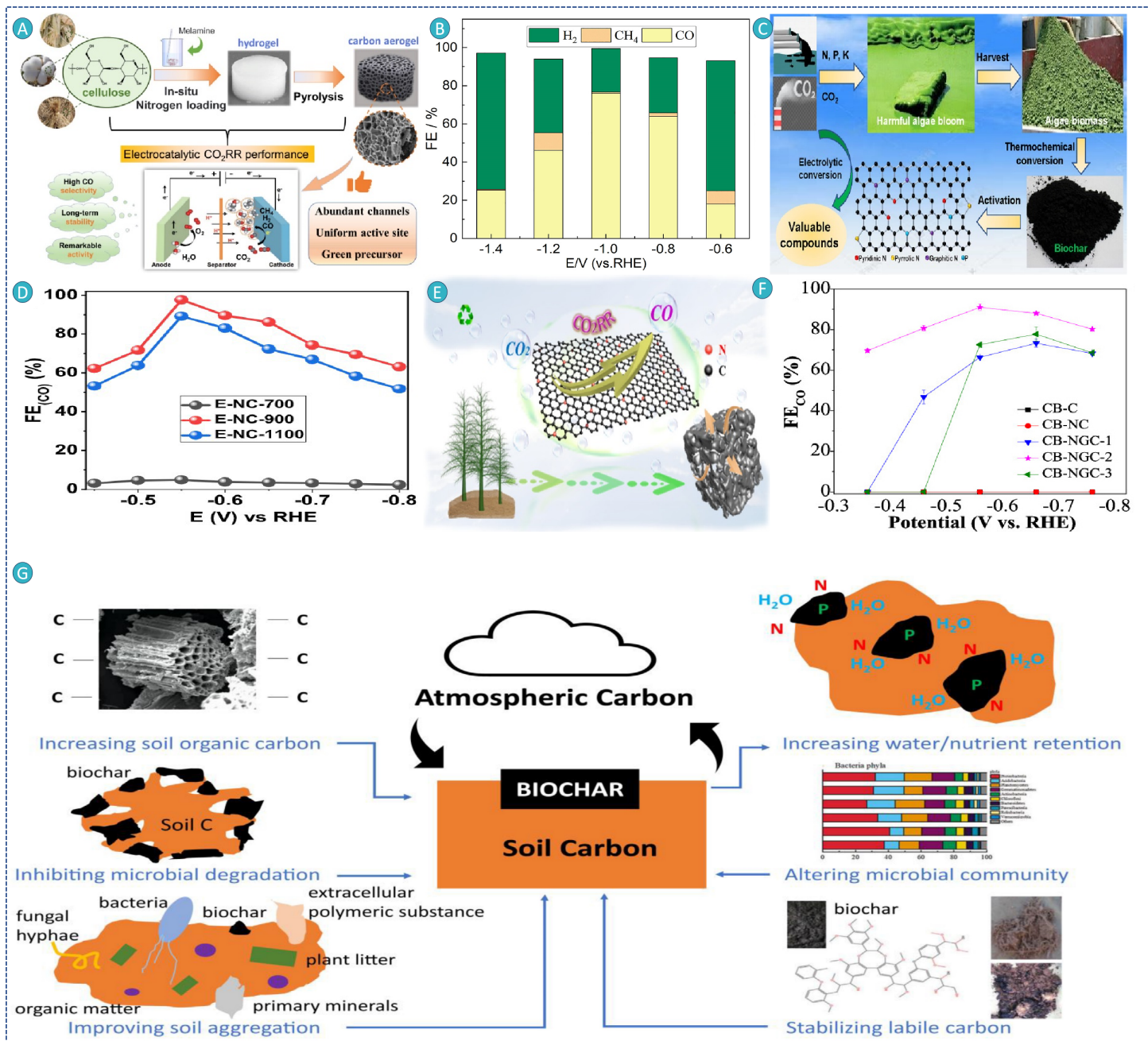


Figure 7. PCMs for electrochemical CO₂ reduction and sequestration (A) Nitrogen-rich carbon aerogel creation via reforming technology.²⁶² Copyright 2023, Elsevier, under CC BY license. (B) FE of N-doped porous carbon aerogel at different carbonization temperatures.²⁶³ Copyright 2023, Elsevier. (C) N-doped carbon from HABs using thermochemical conversion. (D) Electrocatalytic CO₂ RR performance of synthesized N-doped carbon materials.²⁶⁴ Copyright 2023, American Chemical Society. (E) Three-dimensional N-doped graphitized carbon from cedar biomass with high N-doping content. (F) Electrocatalytic CO₂ RR performance of various N-doped carbon electrocatalysts.²⁶⁷ Copyright 2021, American Chemical Society. (G) Biochar's effect on enhancing soil carbon sequestration.²⁶⁹ Copyright 2023, MDPI, under CC BY license.

and climate change mitigation is significant.

CONCLUSIONS, CHALLENGES AND FUTURE PERSPECTIVES

In summary, this review systematically explores strategies to address the challenges in PCMs synthesis, with a focus on sustainable precursors such as biomass and waste biochar. Energy-efficient carbonization techniques are crucial for producing high-quality PCMs while minimizing environmental impact. The incorporation of green activation agents highlights ongoing efforts to modify PCMs synthesis in an eco-friendly manner. A comprehensive LCA offers a holistic perspective on the environmental impact, guiding researchers and practitioners in making informed decisions. This review underscores the diverse applications of PCMs in combating CO₂ emissions, particularly in carbon capture and storage technologies, while acknowledging achievements, challenges, and envisioning future prospects. This analysis serves as a roadmap for the continuous evolution of PCMs synthesis

towards a sustainable and environmentally conscious future. However, despite recent advancements, several challenges remain, along with numerous future perspectives, as outlined below:

Biomass waste is a sustainable and cost-effective source for PCMs synthesis. However, the characterization of biomass precursors is often inadequate, making it difficult to control the structure and properties of the resulting PCMs. This is particularly important for PCMs with controlled pore structures essential for applications such as CO₂ capture and mitigation. Further research is needed to improve the characterization of biomass precursors and develop pretreatment methods that can control the structure and properties of PCMs.

Sustainable biomass conversion requires efficient and eco-friendly carbonization methods. Traditional methods like pyrolysis and HTC, while established, are energy-intensive and time-consuming. Emerging techniques such as LIC and MAC show promise by enhancing efficiency and reducing

processing times. Additionally, exploring low-temperature graphitization methods could further improve energy efficiency and environmental friendliness, advancing biomass conversion processes towards greener practices.

CO₂ capture is vital for mitigating climate change, but many adsorbents exhibit high CO₂ adsorption only under specific conditions of temperature and pressure, limiting their applicability. Adsorbents that maintain high CO₂ adsorption across a broader range of conditions are needed for both pre-combustion and post-combustion CO₂ capture. This would provide greater flexibility in designing and operating CO₂ capture systems.

While KOH and ZnCl₂ are effective activation agents for producing PCMs with superior CO₂ adsorption capabilities, their corrosive and toxic nature poses environmental risks. Green activation methods that can produce porous carbons with high CO₂ adsorption capacities without harmful waste are essential. Physical activation methods using steam, air, or CO₂ offer potential as sustainable alternatives, and future research should focus on optimizing these processes for specific CO₂ capture applications.

A comprehensive understanding of the mechanisms underlying CO₂ adsorption is critical for advancing carbon capture technologies. The role of specific functional groups on the carbon surface, pore structures, and the interactions between CO₂ molecules and the adsorbent are complex and not fully understood. Future research should focus on the thermodynamics and kinetics of CO₂ adsorption processes to optimize and design efficient PCMs tailored for enhanced CO₂ capture.

PCMs with hierarchical pore structures show great potential as electrocatalysts for electrochemical CO₂RR. However, challenges remain, such as understanding the active sites involved in CO₂ conversion and optimizing CO₂ adsorption energies. Further research is needed to elucidate these complexities and fully harness the potential of PCMs electrocatalysts for economically feasible CO₂ reduction processes.

Both CO₂ capture and electrochemical conversion are promising technologies for mitigating greenhouse gas emissions, with the potential to convert CO₂ into valuable products using renewable energy sources. However, current electrochemical approaches are expensive, and there is a need for more effective carbon conversion technologies that can handle large-scale emissions. Further research and development are needed to make these technologies more efficient and cost-effective.

The ultimate goal is to implement these sustainable carbon materials with exceptional properties in practical applications. A critical step is scaling up their production from the laboratory to industrial levels. This necessitates further research and development of simple, eco-friendly manufacturing processes to produce low-cost, environmentally sustainable carbon materials. Addressing these challenges in material synthesis will offer valuable insights for the design of sustainable carbon materials tailored to emerging applications.

REFERENCES

- Roy P., Mohanty A. K. and Misra M. (2023). Prospects of carbon capture, utilization and storage for mitigating climate change. *Environ. Sci. Adv.* **2**:409–423. DOI:10.1039/d2va00236a
- Marescaux A., Thieu V. and Garnier J. (2018). Carbon dioxide, methane and nitrous oxide emissions from the human-impacted Seine watershed in France. *Sci. Total Environ.* **643**:247–259. DOI:10.1016/j.scitotenv.2018.06.151
- Vicente R Barros. C. B. F., David Jon Dokken., et al. (2014). Climate change 2014: Impacts, adaptation and vulnerability (Cambridge University Press). DOI:10.1017/cbo9781107415386
- Dutcher B., Fan M. and Russell A. G. (2015). Amine-based CO₂ capture technology development from the beginning of 2013 -A review. *ACS Appl. Mater. Interfaces* **7**:2137–2148. DOI:10.1021/am507465f
- Gao X., Yang S., Hu L., et al. (2022). Carbonaceous materials as adsorbents for CO₂ capture: synthesis and modification. *Carbon Capture Sci. Technol.* **3**:100039. DOI:10.1016/j.ccst.2022.100039
- Patel H. A., Byun J. and Yavuz C. T. (2017). Carbon dioxide capture adsorbents: chemistry and methods. *ChemSusChem* **10**:1303–1317. DOI:10.1002/cssc.201601545
- Fu D. and Davis M. E. (2022). Carbon dioxide capture with zeotype materials. *Chem. Soc. Rev.* **51**:9340–9370. DOI:10.1039/d2cs00508e
- Sun Z., Liao Y., Zhao S., et al. (2022). Research progress in metal-organic frameworks (MOFs) in CO₂ capture from post-combustion coal-fired flue gas: characteristics, preparation, modification and applications. *J. Mater. Chem. A* **10**:5174–5211. DOI:10.1039/d1ta07856a
- Zeng Y., Zou R. and Zhao Y. (2016). Covalent organic frameworks for CO₂ capture. *Adv. Mater.* **28**:2855–2873. DOI:10.1002/adma.201505004
- Song K. S., Fritz P. W. and Coskun A. (2022). Porous organic polymers for CO₂ capture, separation and conversion. *Chem. Soc. Rev.* **51**:9831–9852. DOI:10.1039/d2cs00727d
- Usman M., Ghanem A. S., Niaz Ali Shah S., et al. (2022). A review on SAPO-34 zeolite materials for CO₂ capture and conversion. *Chem. Rec.* **22**:e202200039. DOI:10.1002/tcr.202200039
- Delgado-Marín J. J., Izan D. P., Molina-Sabio M., et al. (2022). New generation of MOF-monoliths based on metal foams. *Molecules* **27**:1968. DOI:10.3390/molecules27061968
- Jalilov A. S., Li Y. L., Kittrell C., et al. (2017). Increased CO₂ selectivity of asphalt-derived porous carbon through introduction of water into pore space. *Nat. Energy* **2**:932–938. DOI:10.1038/s41560-017-0030-y
- Park J., Kretzschmar A., Selmert V., et al. (2021). Structural study of polyacrylonitrile-based carbon nanofibers for understanding gas adsorption. *ACS Appl. Mater. Interfaces* **13**:46665–46670. DOI:10.1021/acsami.1c13541
- Ali N., Babar A. A., Wang X. F., et al. (2023). Hollow, porous, and flexible Co₃O₄ doped carbon nanofibers for efficient CO₂ capture. *Adv. Eng. Mater.* **25**: DOI:10.1002/adem.202201335
- Shao J. W., Wang Y. Y., Che M. Y., et al. (2025). Sustainable CO₂ capture: N,S-codoped porous carbons derived from petroleum coke with high selectivity and stability. *Molecules* **30**:426. DOI:10.3390/molecules30020426
- Shah S. N. A., Gul E., Nath N. C. D., et al. (2023). Biomass-derived N-doped carbon for electrochemical supercapacitors. Biomass-based supercapacitors: Design, fabrication and sustainability (John Wiley & Sons, Inc). DOI:10.1002/9781119866435.ch17
- Gao F. L., Zhang J. B., Ren M. Y., et al. (2020). Preparation and characterization of porous carbons by pyrolysis-CO₂ gasification of Pine Sawdust. *Chem. Lett.* **49**:652–655. DOI:10.1246/cl.200087
- Wang Z. J., Liu C., Ouyang J., et al. (2025). Porous carbon materials derived from rice husk pyrolysis with NaCl/ Na₂CO₃ binary molten salt for CO₂ capture. *Ind. Crops Prod.* **227**:120808. DOI:10.1016/j.indcrop.2025.120808
- He H., Zhang R., Zhang P., et al. (2023). Functional carbon from nature: Biomass-derived carbon materials and the recent progress of their applications. *Adv. Sci.* **10**:2205557. DOI:10.1002/adv.202205557
- Zhao Y., Cui H. M., Xu J. G., et al. (2025). Synthesis of biomimetic N-doped porous carbons from gelatin using salt template coupled with chemical activation strategy for CO₂ capture. *Chem. Eng. J.* **505**:159241. DOI:10.1016/j.cej.2025.159241
- Yang W., Chen H., Han X., et al. (2020). Preparation of magnetic Co-Fe modified porous carbon from agricultural wastes by microwave and steam activation for mercury removal. *J. Hazard. Mater.* **381**:120981. DOI:10.1016/j.jhazmat.2019.120981
- Jin C., Sun J., Chen Y. N., et al. (2021). Sawdust wastes-derived porous carbons for CO₂ adsorption. Part 1. Optimization preparation via orthogonal experiment. *Sep. Purif. Technol.* **276**:119270. DOI:10.1016/j.seppur.2021.119270
- Yuan X. Z., Wang J. Y., Deng S., et al. (2022). Recent advancements in sustainable upcycling of solid waste into porous carbons for carbon dioxide capture. *Renew. Sustain. Energy Rev.* **162**:112413. DOI:10.1016/j.rser.2022.112413
- Wang W., Wang Z., Jiang L., et al. (2023). Construction of hierarchically porous carbon from plastic waste for CO₂ capture and separation. *Mater. Today Sustain.* **21**:100280. DOI:10.1016/j.mtsust.2022.100280
- Ayele M., Limeneh D. Y., Tesfaye T., et al. (2021). A review on utilization routes of the leather industry biomass. *Adv. Mater. Sci. Eng.* **2021**:1–15. DOI:10.1155/2021/1503524
- Wang Z., Shen D., Wu C., et al. (2018). State-of-the-art on the production and application of carbon nanomaterials from biomass. *Green Chem.* **20**:5031–5057. DOI:10.1039/c8gc01748d
- Sharma H. B., Sarmah A. K. and Dubey B. (2020). Hydrothermal carbonization of renewable waste biomass for solid biofuel production: A discussion on process mechanism, the influence of process parameters, environmental performance and fuel properties of hydrochar. *Renew. Sustain. Energy Rev.* **123**:109761. DOI:10.1016/j.rser.2020.109761
- Wu D. W., Yang Y. J., Liu J., et al. (2020). Plasma-modified N/O-doped porous carbon for CO₂ Capture: An experimental and theoretical study. *Energy & Fuels* **34**:6077–6084. DOI:10.1021/acs.energyfuels.0c00415
- Huang F., Li D. W., Wang L., et al. (2021). Rational introduction of nitridizing agent to hydrothermal carbonization for enhancing CO₂ capture performance of tobacco stalk-based porous carbons. *J. Anal. Appl. Pyrolysis* **157**:105047. DOI:10.1016/j.jaap.2021.105047
- Quan C., Zhou Y., Wang J., et al. (2023). Biomass-based carbon materials for CO₂ capture: A review. *J. CO₂ Util.* **68**:102373. DOI:10.1016/j.jccou.2022.102373
- Le T. S. D., Park S., An J., et al. (2019). Ultrafast laser pulses enable one-step graphene patterning on woods and leaves for green electronics. *Adv. Funct. Mater.* **29**:1902771. DOI:10.1002/adfm.201902771
- Lin J., Peng Z. W., Liu Y. Y., et al. (2014). Laser-induced porous graphene films from commercial polymers. *Nat. Commun.* **5**:5714. DOI:10.1038/ncomms6714
- Shukla N., Sahoo D. and Remya N. (2019). Biochar from microwave pyrolysis of rice

- husk for tertiary wastewater treatment and soil nourishment. *J. Clean. Prod.* **235**:1073–1079. DOI:10.1016/j.jclepro.2019.07.042
35. Zgrzebnicki M., Nair V., Mitra S., et al. (2022). N-doped activated carbon derived from furfuryl alcohol—development of porosity, properties, and adsorption of carbon dioxide and ethene. *Chem. Eng. J.* **427**:131709. DOI:10.1016/j.cej.2021.131709
 36. Zhang W., Cheng R.-r., Bi H.-h., et al. (2021). A review of porous carbons produced by template methods for supercapacitor applications. *New Carbon Mater.* **36**:69–81. DOI:10.1016/j.carbon.2021.02.010
 37. Heidarinejad Z., Dehghani M. H., Heidari M., et al. (2020). Methods for preparation and activation of activated carbon: A review. *Environ. Chem. Lett.* **18**:393–415. DOI:10.1007/s10311-019-00955-0
 38. Liao M., Kelley S. and Yao Y. (2019). Generating energy and greenhouse gas inventory data of activated carbon production using machine learning and kinetic based process simulation. *ACS Sustain. Chem. Eng.* **8**:1252–1261. DOI:10.1021/acssuschemeng.9b06522
 39. Jha G., Soren S. and Mehta K. D. (2020). Life cycle assessment of sintering process for carbon footprint and cost reduction: A comparative study for coke and biomass-derived sintering process. *J. Clean. Prod.* **259**:120889. DOI:10.1016/j.jclepro.2020.120889
 40. Sam D. K., Sam E. K., Durairaj A., et al. (2020). Synthesis of biomass-based carbon aerogels in energy and sustainability. *Carbohydr. Res.* **491**:107986. DOI:10.1016/j.carres.2020.107986
 41. Zhang G., Liu X., Wang L., et al. (2022). Recent advances of biomass derived carbon-based materials for efficient electrochemical energy devices. *J. Mater. Chem. A* **10**:9277–9307. DOI:10.1039/d2ta01442d
 42. Querejeta N., Gil M. V., Rubiera F., et al. (2023). Prospects of low-temperature solid sorbents in industrial CO₂ capture: A focus on biomass residues as precursor material. *Greenh. Gases Sci. Technol.* **13**:245–284. DOI:10.1002/ghg.2210
 43. Morgan J. L., Strumillo J. and Zimmer J. (2013). Crystallographic snapshot of cellulose synthesis and membrane translocation. *Nature* **493**:181–186. DOI:10.1038/nature11744
 44. Li J., Zhang S., Li H., et al. (2018). Cellulase pretreatment for enhancing cold caustic extraction-based separation of hemicelluloses and cellulose from cellulosic fibers. *Bioresour. Technol.* **251**:1–6. DOI:10.1016/j.biortech.2017.12.026
 45. Falco C., Marco-Lozar J. P., Salinas-Torres D., et al. (2013). Tailoring the porosity of chemically activated hydrothermal carbons: Influence of the precursor and hydrothermal carbonization temperature. *Carbon* **62**:346–355. DOI:10.1016/j.carbon.2013.06.017
 46. Fan M., Li C., Shao Y., et al. (2022). Pyrolysis of cellulose: Correlation of hydrophilicity with evolution of functionality of biochar. *Sci. Total Environ.* **825**:153959. DOI:10.2139/ssrn.3967428
 47. Gao T., Xu C., Li R., et al. (2019). Biomass-derived carbon paper to sandwich magnetite anode for long-life Li-ion battery. *ACS Nano* **13**:11901–11911. DOI:10.1021/acsnano.9b05978.s001
 48. Wang D.-C., Yu H.-Y., Qi D., et al. (2021). Confined chemical transitions for direct extraction of conductive cellulose nanofibers with graphitized carbon shell at low temperature and pressure. *J. Am. Chem. Soc.* **143**:11620–11630. DOI:10.1021/jacs.1c04710.s001
 49. Lai H., Zhuo H., Hu Y., et al. (2021). Anisotropic carbon aerogel from cellulose nanofibers featuring highly effective compression stress transfer and pressure sensing. *ACS Sustainable Chem. Eng.* **9**:9761–9769. DOI:10.1021/acssuschemeng.1c02051
 50. Vazhayal L., Wilson P. and Prabhakaran K. (2020). Waste to wealth: Lightweight, mechanically strong and conductive carbon aerogels from waste tissue paper for electromagnetic shielding and CO₂ adsorption. *Chem. Eng. J.* **381**:122628. DOI:10.1016/j.cej.2019.122628
 51. Cheng J., Cheng X., Wang Z., et al. (2023). Multifunctional carbon aerogels from typha orientalis for applications in adsorption: Hydrogen storage, CO₂ capture and VOCs removal. *Energy* **263**:125984. DOI:10.1016/j.energy.2022.125984
 52. Sun H., Yang B. and Li A. (2019). Biomass derived porous carbon for efficient capture of carbon dioxide, organic contaminants and volatile iodine with exceptionally high uptake. *Chem. Eng. J.* **372**:65–73. DOI:10.1016/j.cej.2019.04.061
 53. Junli R., Xinwen P., Linxin Z., et al. (2012). Novel hydrophobic hemicelluloses: Synthesis and characteristic. *Carbohydr. Poly.* **89**:152–157. DOI:10.1016/j.carbpol.2012.02.064
 54. Scheller H. V. and Ulvskov P. (2010). *Annu. Rev. Plant Biol.* **61**:263–289. DOI:10.1146/annurev-arplant-042809-112315
 55. Werner K., Pommer L. and Broström M. (2014). Thermal decomposition of hemicelluloses. *J. Anal. Appl. Pyrolysis* **110**:130–137. DOI:10.1016/j.jaap.2014.08.013
 56. Liu K.-X., Li H.-Q., Zhang J., et al. (2016). The effect of non-structural components and lignin on hemicellulose extraction. *Bioresour. Technol.* **214**:755–760. DOI:10.1016/j.biortech.2016.05.036
 57. Wang Y., Yang R., Li M., et al. (2015). Hydrothermal preparation of highly porous carbon spheres from hemp (*Cannabis sativa* L.) stem hemicellulose for use in energy-related applications. *Ind. Crops Prod.* **65**:216–226. DOI:10.1016/j.indcrop.2014.12.008
 58. Lin H., Liu Y., Chang Z., et al. (2020). A new method of synthesizing hemicellulose-derived porous activated carbon for high-performance supercapacitors. *Micropor. Mesopor. Mater.* **292**:109707. DOI:10.1016/j.micromeso.2019.109707
 59. Lee D.-W., Jin M.-H., Park J.-H., et al. (2018). Flexible synthetic strategies for lignin-derived hierarchically porous carbon materials. *ACS Sustainable Chem. Eng.* **6**:10454–10462. DOI:10.1021/acssuschemeng.8b01811
 60. Puziy A. M., Poddubnaya O. I. and Sevastyanova O. (2018). Carbon materials from technical lignins: Recent advances. *Lignin Chem.* **11**:95–128. DOI:10.1007/s41061-018-0210-7
 61. Yue X., Suopajärvi T., Mankinen O., et al. (2020). Comparison of lignin fractions isolated from wheat straw using alkaline and acidic deep eutectic solvents. *J. Agric. Food Chem.* **68**:15074–15084. DOI:10.1021/acs.jafc.0c04981
 62. Yu O. and Kim K. H. (2020). Lignin to materials: A focused review on recent novel lignin applications. *Appl. Sci.* **10**:4626. DOI:doi.org/10.3390/app10134626. DOI:10.3390/app10134626
 63. Sani S., Liu X., Stevens L., et al. (2023). Amine functionalized lignin-based mesoporous cellular carbons for CO₂ capture. *Fuel* **351**:128886. DOI:10.1016/j.fuel.2023.128886
 64. Zhao B., Borghei M., Zou T., et al. (2021). Lignin-based porous supraparticles for carbon capture. *ACS Nano* **15**:6774–6786. DOI:10.1021/acsnano.0c10307
 65. Zhang B., Song J., Yang G., et al. (2014). Large-scale production of high-quality graphene using glucose and ferric chloride. *Chem. Sci.* **5**:4656–4660. DOI:10.1039/C4SC001950D
 66. Chen Z., Ren W., Gao L., et al. (2011). Three-dimensional flexible and conductive interconnected graphene networks grown by chemical vapour deposition. *Nat. Mater.* **10**:424–428. DOI:10.1038/nmat3001
 67. Mahyari M., Shaabani A., Behbahani M., et al. (2014). Thiol-functionalized fructose-derived nanoporous carbon as a support for gold nanoparticles and its application for aerobic oxidation of alcohols in water. *Appl. Organomet. Chem.* **28**:576–583. DOI:10.1002/aoc.3159
 68. Heckel J. C., Farhan F. F. and Chumanov G. (2008). The effect of fructose derived carbon shells on the plasmon resonance and stability of silver nanoparticles. *Colloid Polym. Sci.* **286**:1545–1552. DOI:10.1007/s00396-008-1929-4
 69. Kurniawan D., Sharma N., Rahardja M. R., et al. (2022). Plasma nanoengineering of bioresource-derived graphene quantum dots as ultrasensitive environmental nanopores. *ACS Appl. Mater. Interfaces* **14**:52289–52300. DOI:10.1021/acsaami.2c15251.s001
 70. Varma R. S. (2019). Biomass-derived renewable carbonaceous materials for sustainable chemical and environmental applications. *ACS Sustainable Chem. Eng.* **7**:6458–6470. DOI:10.1021/acssuschemeng.8b06550
 71. Samar M. M., El-Kalyoubi M., Khalaf M., et al. (2013). Physicochemical, functional, antioxidant and antibacterial properties of chitosan extracted from shrimp wastes by microwave technique. *Ann. Agric. Sci.* **58**:33–41. DOI:10.1016/j.aos.2013.01.006
 72. Yusuf N. L. B. M., Lim L. Y. and Khor E. (2001). Preparation and characterization of chitin beads as a wound dressing precursor. *J. Biomed. Mater. Res.* **54**:59–68. DOI:10.1002/1097-4636(200101)54:1<59::AID-JBM7>3.0.CO;2-U
 73. Wu H., Williams G. R., Wu J., et al. (2018). Regenerated chitin fibers reinforced with bacterial cellulose nanocrystals as suture biomaterials. *Carbohydr. Polym.* **180**:304–313. DOI:10.1016/j.carbpol.2017.10.022
 74. Xu W.-L., Chen H.-J., Wang Y.-C., et al. (2022). Chitin-derived fibrous carbon microspheres as support of polyamine for remarkable CO₂ capture. *Green Chem. Eng.* **3**:267–279. DOI:10.1016/j.gce.2022.01.006
 75. Dassanayake R. S., Gunathilake C., Abidi N., et al. (2018). Activated carbon derived from chitin aerogels: preparation and CO₂ adsorption. *Cellulose* **25**:1911–1920. DOI:10.1007/s10570-018-1660-3
 76. Pakizeh M., Moradi A. and Ghassemi T. (2021). Chemical extraction and modification of chitin and chitosan from shrimp shells. *Eur. Polym. J.* **159**:110709. DOI:10.1016/j.eurpolymj.2021.110709
 77. Kumari S., Annamareddy S. H. K., Abanti S., et al. (2017). Physicochemical properties and characterization of chitosan synthesized from fish scales, crab and shrimp shells. *Int. J. Biol. Macromol.* **104**:1697–1705. DOI:10.1016/j.jbiomac.2017.04.119
 78. Yang Q., Teng D., Qu J., et al. (2021). Solvent-free synthesis of N-doped porous carbons from chitosan for an efficient CO₂ capture. *Ind. Eng. Chem. Res.* **60**:13023–13030. DOI:10.1021/acs.iecr.1c02351
 79. Li J., Bao A., Chen J., et al. (2022). A green route to CO₂ adsorption on biomass chitosan derived nitrogen-doped micropore-dominated carbon nanosheets by different activators. *J. Environ. Chem. Eng.* **10**:107021. DOI:10.1016/j.jece.2021.107021
 80. Rehman A. and Park S.-J. (2020). From chitosan to urea-modified carbons: Tailoring the ultra-microporosity for enhanced CO₂ adsorption. *Carbon* **159**:625–637. DOI:10.1016/j.carbon.2019.12.068
 81. Wang P., Zhang G., Chen W., et al. (2020). Molten salt template synthesis of hierarchical porous nitrogen-containing activated carbon derived from chitosan for CO₂ capture. *ACS Omega* **5**:23460–23467. DOI:10.1021/acsomega.0c03497
 82. Kamran U. and Park S.-J. (2020). Tuning ratios of KOH and NaOH on acetic acid-mediated chitosan-based porous carbons for improving their textural features and CO₂ uptakes. *J. CO₂ Util.* **40**:101212. DOI:10.1016/j.jcou.2020.101212
 83. Kaza S., Yao L., Bhada-Tata P., et al. (2018). What a waste 2.0: A global snapshot of solid waste management to 2050 (World Bank Publications). DOI:10.1596/978-1-

- 4648-1329-Q_ch6
84. EPA (2021). Basic Information about Landfill Gas -Methane Emissions from Landfills (Environmental Protection Agency). <https://www.epa.gov/lmop/basic-information-about-landfill-gas#>
85. Yadav I. C. and Devi N. L. (2019). Biomass burning, regional air quality, and climate change. *Environ. Health* **2**:386–391. DOI:10.1016/B978-0-12-409548-9.11022-X
86. Seo J. Y., Tokmurzin D., Lee D., et al. (2022). Production of biochar from crop residues and its application for biofuel production processes-An overview. *Bioresour. Technol.* **361**:127740. DOI:10.1016/j.biortech.2022.127740
87. Bolan N., Hoang S. A., Beiyuan J., et al. (2022). Multifunctional applications of biochar beyond carbon storage. *Int. Mater. Rev.* **67**:150–200. DOI:10.1080/09506608.2021.1922047
88. Jia M., Wang F., Jin X., et al. (2016). Metal ion–oxytetracycline interactions on maize straw biochar pyrolyzed at different temperatures. *Chem. Eng. J.* **304**:934–940. DOI:10.1016/j.cej.2016.05.064
89. Liu Z., Xu Z., Xu L., et al. (2022). Modified biochar: synthesis and mechanism for removal of environmental heavy metals. *Carbon Res.* **1**:8. DOI:10.1007/s44246-022-00007-3
90. Chen W., Meng J., Han X., et al. (2019). Past, present, and future of biochar. *Biochar* **1**:75–87. DOI:10.1007/s42773-019-00008-3
91. Lehmann J. (2007). A handful of carbon. *Nature* **447**:143–144. DOI:10.1038/447143a
92. Wang J. and Wang S. (2019). Preparation, modification and environmental application of biochar: A review. *J. Clean. Prod.* **227**:1002–1022. DOI:10.1016/j.jclepro.2019.04.282
93. Paramasivan B. (2022). Microwave assisted carbonization and activation of biochar for energy-environment nexus: A review. *Chemosphere* **286**:131631. DOI:10.1016/j.chemosphere.2021.131631
94. Soni B. and Karmee S. K. (2020). Towards a continuous pilot scale pyrolysis based biorefinery for production of biooil and biochar from sawdust. *Fuel* **271**:117570. DOI:10.1016/j.fuel.2020.117570
95. Martín-Lara M., Piñar A., Ligeró A., et al. (2021). Characterization and use of char produced from pyrolysis of post-consumer mixed plastic waste. *Water* **13**:1188. DOI:10.3390/w13091188
96. Singh E., Kumar A., Mishra R., et al. (2021). Pyrolysis of waste biomass and plastics for production of biochar and its use for removal of heavy metals from aqueous solution. *Bioresour. Technol.* **320**:124278. DOI:10.1016/j.biortech.2020.124278
97. Oh S.-Y. and Seo T.-C. (2019). Upgrading biochar via co-pyrolyzation of agricultural biomass and polyethylene terephthalate wastes. *RSC Adv.* **9**:28284–28290. DOI:10.1039/c9ra05518e
98. Ghodake G. S., Shinde S. K., Kadam A. A., et al. (2021). Review on biomass feedstocks, pyrolysis mechanism and physicochemical properties of biochar: State-of-the-art framework to speed up vision of circular bioeconomy. *J. Clean. Prod.* **297**:126645. DOI:10.1016/j.jclepro.2021.126645
99. Dissanayake P. D., You S., Igalavithana A. D., et al. (2020). Biochar-based adsorbents for carbon dioxide capture: A critical review. *Renew. Sustain. Energy Rev.* **119**:109582. DOI:10.1016/j.rser.2019.109582
100. Siedt M., Schäffer A., Smith K. E., et al. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Sci. Total Environ.* **751**:141607. DOI:10.1016/j.scitotenv.2020.141607
101. Shaheen S. M., Niazi N. K., Hassan N. E., et al. (2019). Wood-based biochar for the removal of potentially toxic elements in water and wastewater: a critical review. *Int. Mater. Rev.* **64**:216–247. DOI:10.1080/09506608.2018.1473096
102. Liu G., Sheng H., Fu Y., et al. (2019). Extracellular polymeric substances (EPS) modulate adsorption isotherms between biochar and 2, 2', 4, 4' -tetrabromodiphenyl ether. *Chemosphere* **214**:176–183. DOI:10.1016/j.chemosphere.2018.09.081
103. Jia M., Wang F., Bian Y., et al. (2018). Sorption of sulfamethazine to biochars as affected by dissolved organic matters of different origin. *Bioresour. Technol.* **248**:36–43. DOI:10.1016/j.biortech.2017.08.082
104. Ye L., Camps-Arbestain M., Shen Q., et al. (2020). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use Manage.* **36**:2–18. DOI:10.1111/sum.12546
105. Bruun E. W., Petersen C. T., Hansen E., et al. (2014). Biochar amendment to coarse sandy subsoil improves root growth and increases water retention. *Soil Use Manage.* **30**:109–118. DOI:10.1111/sum.12102
106. Hossain M. Z., Bahar M. M., Sarkar B., et al. (2020). Biochar and its importance on nutrient dynamics in soil and plant. *Biochar* **2**:379–420. DOI:10.1007/s42773-020-00065-z
107. Woolf D., Amonette J. E., Street-Perrott F. A., et al. (2010). Sustainable biochar to mitigate global climate change. *Nat. Commun.* **1**:56. DOI:10.1038/ncomms1053
108. Usman M., Chen H., Chen K., et al. (2019). Characterization and utilization of aqueous products from hydrothermal conversion of biomass for bio-oil and hydrochar production: a review. *Green Chem.* **21**:1553–1572. DOI:doi.org/10.1039/c8gc03957g. DOI:10.1039/C8GC03957G
109. Yuan T., Cheng Y., Zhang Z., et al. (2019). Comparative study on hydrothermal treatment as pre-and post-treatment of anaerobic digestion of primary sludge: Focus on energy balance, resources transformation and sludge dewaterability. *Appl. Energy* **239**:171–180. DOI:10.1016/j.apenergy.2019.01.206
110. González-Arias J., Sánchez M. E., Cara-Jiménez J., et al. (2022). Hydrothermal carbonization of biomass and waste: A review. *Environ. Chem. Lett.* **20**:1–11. DOI:10.1007/s12649-020-01255-3
111. Sevilla M. and Fuertes A. B. (2009). Chemical and structural properties of carbonaceous products obtained by hydrothermal carbonization of saccharides. *Chem–Eur. J.* **15**:4195–4203. DOI:10.1002/chem.200802097
112. Han S., Chi M., Xu X., et al. (2025). From Cellulose to Highly Aromatic Hydrochar: Catalytic Carbonization and Catalytic Aromatization Mechanism of Lanthanide (III) Ions. *Catalysts* **15**:245. DOI:10.3390/catal15030245
113. Reza M. T., Andert J., Wirth B., et al. (2014). Hydrothermal carbonization of biomass for energy and crop production. *Appl. Bioenergy* **1**:11–29. DOI:10.2478/apbi-2014-0001
114. Titirici M.-M., Thomas A. and Antonietti M. (2007). Back in the black: hydrothermal carbonization of plant material as an efficient chemical process to treat the CO₂ problem. *New J. Chem.* **31**:787–789. DOI:10.1039/b616045j
115. Shen Y. (2020). A review on hydrothermal carbonization of biomass and plastic wastes to energy products. *Biomass Bioenergy* **134**:105479. DOI:10.1016/j.biombioe.2020.105479
116. Wang T., Zhai Y., Zhu Y., et al. (2018). A review of the hydrothermal carbonization of biomass waste for hydrochar formation: Process conditions, fundamentals, and physicochemical properties. *Renew. Sustain. Energy Rev.* **90**:223–247. DOI:10.1016/j.rser.2018.03.071
117. Yuan X., Dissanayake P. D., Gao B., et al. (2021). Review on upgrading organic waste to value-added carbon materials for energy and environmental applications. *J. Environ. Manage.* **296**:113128. DOI:10.1016/j.jenvman.2021.113128
118. Le H. S., Chen W.-H., Ahmed S. F., et al. (2022). Hydrothermal carbonization of food waste as sustainable energy conversion path. *Bioresour. Technol.* **363**:127958. DOI:10.1016/j.biortech.2022.127958
119. Su H., Zhou X., Zheng R., et al. (2021). Hydrothermal carbonization of food waste after oil extraction pre-treatment: Study on hydrochar fuel characteristics, combustion behavior, and removal behavior of sodium and potassium. *Sci. Total Environ.* **754**:142192. DOI:10.1016/j.scitotenv.2020.142192
120. Chen T., Ye T., Zhu J., et al. (2021). Small-sized biomass-derived hydrothermal carbon with enriched oxygen groups quickens benzene hydroxylation to phenol with dioxygen. *Appl. Catal. A Gen.* **626**:118356. DOI:10.1016/j.apcata.2021.118356
121. Ma R., Fakudze S., Shang Q., et al. (2021). Catalytic hydrothermal carbonization of pomelo peel for enhanced combustibility of coal/hydrochar blends and reduced CO₂ emission. *Fuel* **304**. DOI:10.1016/j.fuel.2021.121422
122. Singh G., Lakhi K. S., Sil S., et al. (2019). Biomass derived porous carbon for CO₂ capture. *Carbon* **148**:164–186. DOI:10.1016/j.carbon.2019.03.050
123. Kim S., Lee Y., Lin K.-Y. A., et al. (2020). The valorization of food waste via pyrolysis. *J. Clean. Prod.* **259**:120816. DOI:10.1016/j.jclepro.2020.120816
124. Lee X. J., Ong H. C., Gan Y. Y., et al. (2020). State of art review on conventional and advanced pyrolysis of macroalgae and microalgae for biochar, bio-oil and bio-syngas production. *Energy Convers. Manage.* **210**:112707. DOI:10.1016/j.enconman.2020.112707
125. Zhang X., Yang X., Yuan X., et al. (2022). Effect of pyrolysis temperature on composition, carbon fraction and abiotic stability of straw biochars: Correlation and quantitative analysis. *Carbon Res.* **1**:17. DOI:10.1007/s44246-022-00017-1
126. Bhat V. S., Supriya S. and Hegde G. (2019). Biomass derived carbon materials for electrochemical sensors. *J. Electrochem. Soc.* **167**:037526. DOI:10.1149/2.0262003JES
127. Liu Y., Zhang Y., Zhang Y.-q., et al. (2021). Investigation on the structural feature and gasification reactivity of bio-char derived from energy crop. *Fuel* **289**:119904. DOI:10.1016/j.fuel.2020.119904
128. Yuan T., He W., Yin G., et al. (2020). Comparison of bio-chars formation derived from fast and slow pyrolysis of walnut shell. *Fuel* **261**:116450. DOI:10.1016/j.fuel.2019.116450
129. Pariyar P., Kumari K., Jain M. K., et al. (2020). Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application. *Sci. Total Environ.* **713**:136433. DOI:10.1016/j.scitotenv.2019.136433
130. Yang P., Guo W., Yu Z., et al. (2023). Modified network kinetic model for coal pyrolysis with high-value products and low carbon emissions. *Appl. Energy* **351**:121763. DOI:10.1016/j.apenergy.2023.121763
131. Yogalakshmi K., Sivashanmugam P., Kavitha S., et al. (2022). Lignocellulosic biomass-based pyrolysis: A comprehensive review. *Chemosphere* **286**:131824. DOI:10.1016/j.chemosphere.2021.131824
132. Yu S., Wang L., Li Q., et al. (2022). Sustainable carbon materials from the pyrolysis of lignocellulosic biomass. *Mater. Today Sustain.* **19**:100209. DOI:10.1016/j.mtsust.2022.100209
133. Niu M., Yao Y., Shi Y., et al. (2019). Multifunctional green sensor prepared by direct laser writing of modified wood component. *Ind. Eng. Chem. Res.* **58**:10364–10372. DOI:10.1021/acs.iecr.9b00850
134. Chyan Y., Ye R., Li Y., et al. (2018). Laser-induced graphene by multiple lasing:

- Toward electronics on cloth, paper, and food. *ACS Nano* **12**:2176–2183. DOI:10.1021/acsnano.7b08539
135. Vashisth A., Kowalik M., Geringer J. C., et al. (2020). ReaxFF simulations of laser-induced graphene (LIG) formation for multifunctional polymer nanocomposites. *ACS Appl. Nano Mater.* **3**:1881–1890. DOI:10.1021/acsnm.9b02524
136. Wang H., Zhao Z., Liu P., et al. (2022). Laser-induced graphene based flexible electronic devices. *Biosensors* **12**:55. DOI:10.3390/bios12020055
137. Duy L. X., Peng Z., Li Y., et al. (2018). Laser-induced graphene fibers. *Carbon* **126**:472–479. DOI:10.1016/j.carbon.2017.10.036
138. Wang N., Bo X. and Zhou M. (2021). Laser conversion of biomass into porous carbon composite under ambient condition for pH-Universal electrochemical hydrogen evolution reaction. *J. Colloid Interface Sci.* **604**:885–893. DOI:10.1016/j.jcis.2021.07.057
139. Ramirez-Rico J., Gutierrez-Pardo A., Martinez-Fernandez J., et al. (2016). Thermal conductivity of Fe graphitized wood derived carbon. *Mater. Des.* **99**:528–534. DOI:10.1016/j.matdes.2016.03.070
140. Johnson M. T. and Faber K. T. (2011). Catalytic graphitization of three-dimensional wood-derived porous scaffolds. *J. Mater. Res.* **26**:18–25. DOI:10.1557/jmr.2010.88
141. Arpia A. A., Chen W.-H., Lam S. S., et al. (2021). Sustainable biofuel and bioenergy production from biomass waste residues using microwave-assisted heating: A comprehensive review. *Chem. Eng. J.* **403**:126233. DOI:10.1016/j.cej.2020.126233
142. Zulkornain M. F., Shamsuddin A. H., Normanbhay S., et al. (2021). Microwave-assisted hydrothermal carbonization for solid biofuel application: A brief review. *Carbon Capture Sci. Technol.* **1**:100014. DOI:10.1016/j.ccst.2021.100014
143. Orbecido A., Lawas K. I., Doliente S., et al. (2019). Parametric study of corn cob biochar (CCBs) yield via microwave pyrolysis. *MATEC Web Conf.* **268**:04005. DOI:10.1051/mateconf/201926804005
144. Dai L., Wang Y., Liu Y., et al. (2020). Microwave-assisted pyrolysis of formic acid pretreated bamboo sawdust for bio-oil production. *Environ Res* **182**:108988. DOI:10.1016/j.envres.2019.108988
145. Kostas E. T., Williams O. S. A., Duran-Jimenez G., et al. (2019). Microwave pyrolysis of *Laminaria digitata* to produce unique seaweed-derived bio-oils. *Biomass Bioenergy* **125**:41–49. DOI:10.1016/j.biombioe.2019.04.006
146. Lin J., Ma R., Luo J., et al. (2020). Microwave pyrolysis of food waste for high-quality syngas production: Positive effects of a CO₂ reaction atmosphere and insights into the intrinsic reaction mechanisms. *Energy Convers. Manage.* **206**:112490. DOI:10.1016/j.enconman.2020.112490
147. Lan G., Yang J., Ye R. P., et al. (2021). Sustainable Carbon Materials toward Emerging Applications. *Small Methods* **5**:e2001250. DOI:10.1002/smtd.202001250
148. Isahak W. N. R. W., Hisham M. W. M. and Yarmo M. A. (2013). Highly porous carbon materials from biomass by chemical and carbonization method: A comparison study. *J. Chem.* **2013**:620346. DOI:10.1155/2013/620346
149. Kesavan G. and Chen S.-M. (2020). Carbon-modified kaolin clay using sugar dehydration technique for the electrochemical detection of quercetin. *J. Mater. Sci.: Mater. Electron.* **31**:21670–21681. DOI:10.1007/s10854-020-04680-1
150. Shan X., Xiong M., Sheng Y., et al. (2020). Concentrated Acid-Induced Dehydration of Fallen Leaves for Efficient, Sustainable, and Self-Cleaning Solar Steam Generation. *Adv. Energy Sustain. Res.* **1**:2000034. DOI:10.1002/aesr.202000034
151. Wang C., Wu D., Wang H., et al. (2018). A green and scalable route to yield porous carbon sheets from biomass for supercapacitors with high capacity. *J. Mater. Chem. A* **6**:1244–1254. DOI:10.1039/c7ta07579k
152. Béguin F., Presser V., Balducci A., et al. (2014). Carbons and electrolytes for advanced supercapacitors. *Adv. Mater.* **26**:2219–2251. DOI:10.1002/adma.201304137
153. Sevilla M., Díez N. and Fuertes A. B. (2021). More sustainable chemical activation strategies for the production of porous carbons. *ChemSusChem* **14**:94–117. DOI:10.1002/cssc.202001838
154. Huang F.-C., Lee C.-K., Han Y.-L., et al. (2014). Preparation of activated carbon using micro-nano carbon spheres through chemical activation. *J. Taiwan Inst. Chem. Eng.* **45**:2805–2812. DOI:10.1016/j.jtice.2014.08.004
155. McKee D. W. (1983). Mechanisms of the alkali metal catalysed gasification of carbon. *Fuel* **62**:170–175. DOI:10.1016/0016-2361(83)90192-8
156. Hayashi J. I., Horikawa T., Takeda I., et al. (2002). Preparing activated carbon from various nutshells by chemical activation with K₂CO₃. *Carbon* **40**:2381–2386. DOI:10.1016/s0008-6223(02)00118-5
157. Sevilla M. and Fuertes A. B. (2016). A green approach to high-performance supercapacitor electrodes: The chemical activation of hydrochar with potassium bicarbonate. *ChemSusChem* **9**:1880–1888. DOI:10.1002/cssc.201600426
158. Díez N., Ferrero G. A., Fuertes A. B., et al. (2019). Sustainable salt template-assisted chemical activation for the production of porous carbons with enhanced power handling ability in supercapacitors. *Batteries Supercaps* **2**:701–711. DOI:10.1002/batt.201900037
159. Ioannidou O. and Zabaniotou A. (2007). Agricultural residues as precursors for activated carbon production—A review. *Renew. Sustain. Energy Rev.* **11**:1966–2005. DOI:10.1016/j.rser.2006.03.013
160. Heo Y.-J. and Park S.-J. (2015). A role of steam activation on CO₂ capture and separation of narrow microporous carbons produced from cellulose fibers. *Energy* **91**:142–150. DOI:10.1016/j.energy.2015.08.033
161. Igalavithana A. D., Choi S. W., Shang J., et al. (2020). Carbon dioxide capture in biochar produced from pine sawdust and paper mill sludge: Effect of porous structure and surface chemistry. *Sci. Total Environ.* **739**:139845. DOI:10.1016/j.scitotenv.2020.139845
162. Lee J. H., Sim S. J., Kang J. H., et al. (2021). Isotherm and thermodynamic modelling of malachite green on CO₂-activated carbon fibers. *Chem. Phys. Lett.* **780**:138962. DOI:10.1016/j.cplett.2021.138962
163. Kozyatnyk I., Oesterle P., Wurzer C., et al. (2021). Removal of contaminants of emerging concern from multicomponent systems using carbon dioxide activated biochar from lignocellulosic feedstocks. *Bioresour. Technol.* **340**:125561. DOI:10.1016/j.biortech.2021.125561
164. Hong S.-M., Yoon H. J., Choi Y., et al. (2020). Solving two environmental problems simultaneously: Scalable production of carbon microspheres from structured packing peanuts with tailored microporosity for efficient CO₂ capture. *Chem. Eng. J.* **379**:122219. DOI:10.1016/j.cej.2019.122219
165. Sevilla M., Ferrero G. A. and Fuertes A. B. (2017). One-pot synthesis of biomass-based hierarchical porous carbons with a large porosity development. *Chem. Mater.* **29**:6900–6907. DOI:10.1021/acs.chemmater.7b02218
166. Li X., Guan B. Y., Gao S., et al. (2019). A general dual-templating approach to biomass-derived hierarchically porous heteroatom-doped carbon materials for enhanced electrocatalytic oxygen reduction. *Energy Environ. Sci.* **12**:648–655. DOI:10.1039/c8ee02779j
167. Chen C., Wang H., Han C., et al. (2017). Asymmetric flasklike hollow carbonaceous nanoparticles fabricated by the synergistic interaction between soft template and biomass. *J. Am. Chem. Soc.* **139**:2657–2663. DOI:10.1021/jacs.6b10841
168. Nelson K. M., Mahurin S. M., Mayes R. T., et al. (2016). Preparation and CO₂ adsorption properties of soft-templated mesoporous carbons derived from chestnut tannin precursors. *Microporous Mesoporous Mater.* **222**:94–103. DOI:10.1016/j.micromeso.2015.09.050
169. Yang B., Zhang D., He J., et al. (2020). Simple and green fabrication of a biomass-derived N and O self-doped hierarchical porous carbon via a self-activation route for supercapacitor application. *Carbon Lett.* **30**:709–719. DOI:10.1007/s42823-020-00143-z
170. Smith L. M., Shi S. Q., Shi J., et al. (2020). Effect of wood species on the pore volume and surface area of activated carbon derived from the self-activation process. *Wood Fiber Sci.* **52**:191–207. DOI:10.22382/wfs-2020-017
171. Zhang Y., Liu S., Zheng X., et al. (2017). Biomass organs control the porosity of their pyrolyzed carbon. *Adv. Funct. Mater.* **27**:1604687. DOI:10.1002/adfm.201604687
172. Kleszyk P., Ratajczak P., Skowron P., et al. (2015). Carbons with narrow pore size distribution prepared by simultaneous carbonization and self-activation of tobacco stems and their application to supercapacitors. *Carbon* **81**:148–157. DOI:10.1016/j.carbon.2014.09.043
173. Bommier C., Xu R., Wang W., et al. (2015). Self-activation of cellulose: A new preparation methodology for activated carbon electrodes in electrochemical capacitors. *Nano Energy* **13**:709–717. DOI:10.1016/j.nanoen.2015.03.022
174. Xia C. and Shi S. Q. (2016). Self-activation for activated carbon from biomass: theory and parameters. *Green Chem.* **18**:2063–2071. DOI:10.1039/c5gc02152a
175. Inagaki M., Nishikawa T., Sakuratani K., et al. (2004). Carbonization of kenaf to prepare highly-microporous carbons. *Carbon* **4**:890–893. DOI:10.1016/j.carbon.2004.01.055
176. Raymundo-Piñero E., Cadek M. and Béguin F. (2009). Tuning carbon materials for supercapacitors by direct pyrolysis of seaweeds. *Adv. Funct. Mater.* **19**:1032–1039. DOI:10.1002/adfm.200801057
177. He J., Zhang D., Han M., et al. (2019). One-step large-scale fabrication of nitrogen doped microporous carbon by self-activation of biomass for supercapacitors application. *J. Energy Storage* **21**:94–104. DOI:10.1016/j.est.2018.11.015
178. Liang C., Li Z. and Dai S. (2008). Mesoporous carbon materials: synthesis and modification. *Angew. Chem. Int. Ed.* **47**:3696–3717. DOI:10.3390/catal13010002
179. Liang H.-W., Wei W., Wu Z.-S., et al. (2013). Mesoporous metal–nitrogen-doped carbon electrocatalysts for highly efficient oxygen reduction reaction. *J. Am. Chem. Soc.* **135**:16002–16005. DOI:10.1021/ja407552k
180. Schmidt-Winkel P., Lukens W. W., Zhao D., et al. (1999). Mesocellular siliceous foams with uniformly sized cells and windows. *J. Am. Chem. Soc.* **121**:254–255. DOI:10.1021/ja983218i
181. Kyotani T., Nagai T., Inoue S., et al. (1997). Formation of new type of porous carbon by carbonization in zeolite nanochannels. *Chem. Mater.* **9**:609–615. DOI:10.1021/cm960430h
182. Kyotani T., Ma Z. and Tomita A. (2003). Template synthesis of novel porous carbons using various types of zeolites. *Carbon* **41**:1451–1459. DOI:10.1016/s0008-6223(03)00090-3
183. Xie K., Qin X., Wang X., et al. (2012). Carbon nanocages as supercapacitor electrode materials. *Adv. Mater.* **24**:347–352. DOI:10.1002/adma.201103872
184. Zhu C., Takata M., Aoki Y., et al. (2018). Nitrogen-doped porous carbon as-mediated by a facile solution combustion synthesis for supercapacitor and oxygen reduction electrocatalyst. *Chem. Eng. J.* **350**:278–289. DOI:10.1016/j.cej.2018.06.001
185. Liang Y., Schwab M. G., Zhi L., et al. (2010). Direct access to metal or metal oxide nanocrystals integrated with one-dimensional nanoporous carbons for electrochemical energy storage. *J. Am. Chem. Soc.* **132**:15030–15037. DOI:10.1021/

- ja106612d
186. Fang Y., Lv Y., Che R., et al. (2013). Two-dimensional mesoporous carbon nanosheets and their derived graphene nanosheets: synthesis and efficient lithium ion storage. *J. Am. Chem. Soc.* **135**:1524–1530. DOI:10.1021/ja310849c
 187. Schacht S., Huo Q., Voigt-Martin I., et al. (1996). Oil-water interface templating of mesoporous macroscale structures. *Science* **273**:768–771. DOI:10.1126/science.273.5276.768
 188. Liu H., Jia M., Yue S., et al. (2017). Creative utilization of natural nanocomposites: nitrogen-rich mesoporous carbon for a high-performance sodium ion battery. *J. Mater. Chem. A* **5**:9572–9579. DOI:10.1039/c7ta01891f
 189. Long X., Li Z., Gao G., et al. (2020). Graphitic phosphorus coordinated single Fe atoms for hydrogenative transformations. *Nat. Commun.* **11**:4074. DOI:10.1038/s41467-020-17903-0
 190. Liang G., Zhu L., Xu J., et al. (2013). Investigations of poly (pyrrole)-coated cotton fabrics prepared in blends of anionic and cationic surfactants as flexible electrode. *Electrochim. Acta* **103**:9–14. DOI:10.1016/j.electacta.2013.04.065
 191. Qiu Y., Hou M., Gao J., et al. (2019). One-step synthesis of monodispersed mesoporous carbon nanospheres for high-performance flexible quasi-solid-state micro-supercapacitors. *Small* **15**:1903836. DOI:10.1002/sml.201903836
 192. Lin J., Yao L., Li Z., et al. (2019). Hybrid hollow spheres of carbon@Co_xNi_{1-x}MoO₄ as advanced electrodes for high-performance asymmetric supercapacitors. *Nanoscale* **11**:3281–3291. DOI:10.1039/c8nr09497g
 193. Li H., Zhao Y., Liu S., et al. (2020). Hierarchical porous carbon monolith derived from lignin for high areal capacitance supercapacitors. *Micropor. Mesopor. Mater.* **297**:109960. DOI:10.1016/j.micromeso.2019.109960
 194. Zhou M. Y., Lin Y. Q., Xia H. Y., et al. (2020). A molecular foaming and activation strategy to porous N-doped carbon foams for supercapacitors and CO₂ Capture. *Nano-Micro Lett.* **12**:58. DOI:10.1007/s40820-020-0389-3
 195. Lee K. K., Church T. L. and Hedin N. (2018). RNA as a precursor to N-doped activated carbon. *ACS Appl. Energy Mater.* **1**:3815–3825. DOI:10.1021/acsaem.8b00589
 196. Fujiki J. and Yogo K. (2016). The increased CO₂ adsorption performance of chitosan-derived activated carbons with nitrogen-doping. *Chem. Commun.* **52**:186–189. DOI:10.1039/c5cc06934c
 197. Islam M. A., Bao H. Y., Saha B. B., et al. (2024). Improved CO₂ capture capacity of waste sawmill dust derived activated carbon employing novel high-pressure CO₂ activation. *Therm. Sci. Eng. Prog.* **56**:103075. DOI:10.1016/j.tsep.2024.103075
 198. Gao Q., Feng Z., He Y., et al. (2023). Pyrolysis self-activation: An environmentally friendly method to transform biowaste into activated carbon for arsenic removal. *Bioresour. Technol.* **368**:128353. DOI:10.1016/j.biortech.2022.128353
 199. Zhao X. B., He T., Wang S. N., et al. (2025). N-doped activated carbon for enhanced CO₂ sorption through self-activation. *Biomass Convers. Biorefin.* **15**:21437–21454. DOI:10.1007/s13399-025-06732-0
 200. Jia H., Du T., Fang X., et al. (2021). Synthesis of template-free ZSM-5 from rice husk ash at low temperatures and its CO₂ adsorption performance. *ACS Omega* **6**:3961–3972. DOI:10.1021/acsomega.0c05842
 201. Jin Z. H., Jiang X., Dai Z. D., et al. (2020). Continuous synthesis of nanodroplet-templated, N-doped microporous carbon spheres in microfluidic system for CO₂ capture. *ACS Appl. Mater. Interfaces* **12**:52571–52580. DOI:10.1021/acsaami.0c14044
 202. Klunk M. A., Das M., Dasgupta S., et al. (2021). Synthesis of ZSM-5 zeolite from metakaolin and rice husk ash to CO₂ adsorption. *ECS J. Solid State Sci. Technol.* **10**:013001. DOI:10.1149/2162-8777/abdb18
 203. Toprak A. and Kopac T. (2017). Carbon dioxide adsorption using high surface area activated carbons from local coals modified by KOH, NaOH and ZnCl₂ agents. *Int. J. Chem. React. Eng.* **15**:20160042. DOI:10.1515/ijcre-2016-0042
 204. Adibfar M., Kaghazchi T., Asasian N., et al. (2014). Conversion of poly(Ethylene Terephthalate) waste into activated carbon: Chemical activation and characterization. *Chem. Eng. Technol.* **37**:979–986. DOI:10.1002/ceat.201200719
 205. Zhang C., Ji Y., Li C. C., et al. (2023). The application of biochar for CO₂ capture: Influence of biochar preparation and CO₂ capture reactors. *Ind. Eng. Chem. Res.* **62**:16945–17368. DOI:10.1021/acs.iecr.3c00445
 206. Wang G. B., Leus K., Zhao S. N., et al. (2018). Newly designed covalent triazine framework based on novel N-heteroaromatic building blocks for efficient CO₂ and H₂ capture and storage. *ACS Appl. Mater. Interfaces* **10**:1244–1249. DOI:10.1021/acsaami.7b16239
 207. Sing G., Ramadass K., Lee J. M., et al. (2019). Convenient design of porous and heteroatom self-doped carbons for CO₂ capture. *Micropor. Mesopor. Mater.* **287**:1–8. DOI:10.1016/j.micromeso.2019.05.042
 208. Zhang W., Li W. and Li S. (2023). Self-template activated carbons for aqueous supercapacitors. *Sustain. Mater. Technol.* **36**:e00582. DOI:10.1016/j.susmat.2023.e00582
 209. Lin R., Li A., Lu L., et al. (2015). Preparation of bulk sodium carboxymethyl cellulose aerogels with tunable morphology. *Carbohydr. Polym.* **118**:126–132. DOI:10.1016/j.carbpol.2014.10.075
 210. Li W., Zhang F., Dou Y. Q., et al. (2011). A self-template strategy for the synthesis of mesoporous carbon nanofibers as advanced supercapacitor electrodes. *Adv. Energy Mater.* **1**:382–386. DOI:10.1002/aenm.201000096
 211. Abioye A. M. and Ani F. N. (2015). Recent development in the production of activated carbon electrodes from agricultural waste biomass for supercapacitors: A review. *Renew. Sustain. Energy Rev.* **52**:1282–1293. DOI:10.1016/j.rser.2015.07.129
 212. Zhang W., Liu Y., Lu G., et al. (2015). Mesoporous metal–organic frameworks with size-, shape-, and space-distribution-controlled pore structure. *Adv. Mater.* **27**:2923–2929. DOI:10.1002/adma.201405752
 213. Ye R., James D. K. and Tour J. M. (2018). Laser-induced graphene. *Acc. Chem. Res.* **51**:1609–1620. DOI:10.1021/acs.accounts.8b00084
 214. Huang Y.-F., Chiu P.-T. and Lo S.-L. (2016). A review on microwave pyrolysis of lignocellulosic biomass. *Sustain. Environ. Res.* **26**:103–109. DOI:10.1016/j.serj.2016.04.012
 215. Vilen A., Laurell P. and Vahala R. (2022). Comparative life cycle assessment of activated carbon production from various raw materials. *J. Environ. Manage.* **324**:116356. DOI:10.1016/j.jenvman.2022.116356
 216. Azadi E. and Dinari M. (2023). Green synthesis, characterization, and properties of carbon aerogels. In *Green Carbon Materials for Environmental Analysis: Emerging Research and Future Opportunities (ACS Publications)* **1441**:1–23. DOI:10.1021/bk-2023-1441.ch001
 217. Reza M. S., Yun C. S., Afroz S., et al. (2020). Preparation of activated carbon from biomass and its applications in water and gas purification, a review. *Arab J. Basic Appl. Sci.* **27**:208–238. DOI:10.1080/25765299.2020.1766799
 218. Yahya M. A., Al-Qodah Z. and Ngah C. Z. (2015). Agricultural bio-waste materials as potential sustainable precursors used for activated carbon production: A review. *Renew. Sustain. Energy Rev.* **46**:218–235. DOI:10.1016/j.rser.2015.02.051
 219. Joseph B., Kaetzl K., Hensgen F., et al. (2020). Sustainability assessment of activated carbon from residual biomass used for micropollutant removal at a full-scale wastewater treatment plant. *Environ. Res. Lett.* **15**:064023. DOI:10.1088/1748-9326/ab8330
 220. Kim M. H., Jeong I. T., Park S. B., et al. (2019). Analysis of environmental impact of activated carbon production from wood waste. *Environ. Eng. Res.* **24**:117–126. DOI:10.4491/eer.2018.104
 221. Zhu X., Labianca C., He M., et al. (2022). Life-cycle assessment of pyrolysis processes for sustainable production of biochar from agro-residues. *Bioresour. Technol.* **360**:127601. DOI:10.1016/j.biortech.2022.127601
 222. Cao B., Jiang D., Zheng Y., et al. (2022). Evaluation of biochar-derived carbocatalysts for pyrolytic conversion of sawdust: Life cycle assessment towards monophenol production. *Fuel* **330**:125476. DOI:10.1016/j.fuel.2022.125476
 223. Arena N., Lee J. and Clift R. (2016). Life Cycle Assessment of activated carbon production from coconut shells. *J. Clean. Prod.* **125**:68–77. DOI:10.1016/j.jclepro.2016.03.073
 224. Cossutta M., Vretenar V., Centeno T. A., et al. (2020). A comparative life cycle assessment of graphene and activated carbon in a supercapacitor application. *J. Clean. Prod.* **242**:118468. DOI:10.1016/j.jclepro.2019.118468
 225. Allangawi A., Alzaimoor E. F. H., Shanaah H. H., et al. (2023). Carbon capture materials in post-combustion: Adsorption and absorption-based processes. *C* **9**:17. DOI:10.3390/c9010017
 226. Al-Mamoori A., Krishnamurthy A., Rownaghi A. A., et al. (2017). Carbon capture and utilization update. *Energy Technol.* **5**:834–849. DOI:10.1002/ente.201600747
 227. Fu L., Ren Z., Si W., et al. (2022). Research progress on CO₂ capture and utilization technology. *J. CO₂ Util.* **66**:102260. DOI:10.1016/j.jcou.2022.102260
 228. Godin J., Liu W., Ren S., et al. (2021). Advances in recovery and utilization of carbon dioxide: A brief review. *J. Environ. Chem. Eng.* **9**:103723. DOI:10.1016/j.jece.2021.105644
 229. Zhiqiang Z., ZHANG H. and Chang J. (2021). Review on global CCUS technology and application. *Mod. Chem. Ind.* **41**:5–10. DOI:10.46855/energy-proceedings-10540
 230. Rashidi N. A. and Yusup S. (2016). An overview of activated carbons utilization for the post-combustion carbon dioxide capture. *J. CO₂ Util.* **13**:1–16. DOI:10.1016/j.jcou.2015.11.002
 231. Serafin J., Ouzzine M., Cruz O. F., Jr., et al. (2021). Conversion of fruit waste-derived biomass to highly microporous activated carbon for enhanced CO₂ capture. *Waste Manag.* **136**:273–282. DOI:10.1016/j.wasman.2021.10.025
 232. Wang F., Harindintwali J. D., Yuan Z., et al. (2021). Technologies and perspectives for achieving carbon neutrality. *The Innovation* **2**:100180. DOI:10.1016/j.xinn.2021.100180
 233. Sevilla M. and Fuertes A. B. (2011). Sustainable porous carbons with a superior performance for CO₂ capture. *Energy Environ. Sci.* **4**:1765–1771. DOI:10.1039/c0ee00784f
 234. Sevilla M., Parra J. B. and Fuertes A. B. (2013). Assessment of the role of micropore size and N-doping in CO₂ capture by porous carbons. *ACS Appl. Mater. Interfaces* **5**:6360–6368. DOI:10.1021/am401423b
 235. Singh G., Lakhi K. S., Kim I. Y., et al. (2017). Highly efficient method for the synthesis of activated mesoporous biocarbons with extremely high surface area for high-pressure CO₂ adsorption. *ACS Appl. Mater. Interfaces* **9**:29782–29793. DOI:10.1021/acsaami.7b08797.s001
 236. Singh G., Kim I. Y., Lakhi K. S., et al. (2017). Heteroatom functionalized activated porous biocarbons and their excellent performance for CO₂ capture at high pressure. *J. Mater. Chem. A* **5**:21196–21204. DOI:10.1039/c7ta07186h
 237. Singh G., Kim I. Y., Lakhi K. S., et al. (2017). Single step synthesis of activated bio-

- carbons with a high surface area and their excellent CO₂ adsorption capacity. *Carbon* **116**:448–455. DOI:10.1016/j.carbon.2017.02.015
238. Serafin J., Dziejarski B., Junior O. F. C., et al. (2023). Design of highly microporous activated carbons based on walnut shell biomass for H₂ and CO₂ storage. *Carbon* **201**:633–647. DOI:10.1016/j.carbon.2022.09.013
 239. Vazhayal L., Wilson P. and Prabhakaran K. (2022). Utilization of waste aquatic weeds for the sustainable production of nitrogen doped nanoporous carbon for CO₂ capture. *Mater. Today Proc.* **52**:2315–2321. DOI:10.1016/j.matpr.2021.11.343
 240. Wang X., Hui W., Hu A., et al. (2021). A synthesis of porous activated carbon materials derived from vitamin B9 base for CO₂ capture and conversion. *Mater. Today Chem.* **20**:100468. DOI:10.1016/j.mtchem.2021.100468
 241. Song C., Ye W., Liu Y., et al. (2020). Facile preparation of porous carbon derived from industrial biomass waste as an efficient CO₂ adsorbent. *ACS Omega* **5**:28255–28263. DOI:10.1021/acsomega.0c04165
 242. Ma X., Chen R., Zhou K., et al. (2020). Activated porous carbon with an ultrahigh surface area derived from waste biomass for acetone adsorption, CO₂ capture, and light hydrocarbon separation. *ACS Sustain. Chem. Eng.* **8**:11721–11728. DOI:10.1021/acssuschemeng.0c03725.s001
 243. Balou S., Babak S. E. and Priye A. (2020). Synergistic effect of nitrogen doping and ultra-microporosity on the performance of biomass and microalgae-derived activated carbons for CO₂ capture. *ACS Appl. Mater. Interfaces* **12**:42711–42722. DOI:10.1021/acscami.0c10218
 244. Singh G., Bahadur R., Lee J. M., et al. (2021). Nanoporous activated biocarbons with high surface areas from alligator weed and their excellent performance for CO₂ capture at both low and high pressures. *Chem. Eng. J.* **406**:126787. DOI:10.1016/j.cej.2020.126787
 245. Ismail I. S., Singh G., Smith P., et al. (2020). Oxygen functionalized porous activated biocarbons with high surface area derived from grape marc for enhanced capture of CO₂ at elevated-pressure. *Carbon* **160**:113–124. DOI:10.1016/j.carbon.2020.01.008
 246. Talapaneni S. N., Lee J. H., Je S. H., et al. (2017). Chemical blowing approach for ultramicroporous carbon nitride frameworks and their applications in gas and energy storage. *Adv. Funct. Mater.* **27**:1604658. DOI:10.1002/adfm.201604658
 247. Vargas D. P., Giraldo L. and Moreno-Piraján J. (2012). CO₂ adsorption on granular and monolith carbonaceous materials. *J. Anal. Appl. Pyrolysis* **96**:146–152. DOI:10.1016/j.jaap.2012.03.016
 248. Zhang X., Elsayed I., Nayanathara R. O., et al. (2022). Biobased hierarchically porous carbon featuring micron-sized honeycomb architecture for CO₂ capture and water remediation. *J. Environ. Chem. Eng.* **10**:107460. DOI:10.1016/j.jece.2022.107460
 249. Zhang Z., Cano Z. P., Luo D., et al. (2019). Rational design of tailored porous carbon-based materials for CO₂ capture. *J. Mater. Chem. A* **7**:20985–21003. DOI:10.1039/c9ta07297g
 250. Li Y., Liu N., Zhang T., et al. (2020). Highly microporous nitrogen-doped carbons from anthracite for effective CO₂ capture and CO₂/CH₄ separation. *Energy* **211**:118561. DOI:10.1016/j.energy.2020.118561
 251. Chen J., Yang J., Hu G., et al. (2016). Enhanced CO₂ capture capacity of nitrogen-doped biomass-derived porous carbons. *ACS Sustainable Chem. Eng.* **4**:1439–1445. DOI:10.1021/acssuschemeng.5b01425
 252. Chen T., Deng S., Wang B., et al. (2015). CO₂ adsorption on crab shell derived activated carbons: contribution of micropores and nitrogen-containing groups. *RSC Adv.* **5**:48323–48330. DOI:10.1039/c5ra04937g
 253. Maliutina K., Tahmasebi A. and Yu J. (2018). Pressurized entrained-flow pyrolysis of microalgae: enhanced production of hydrogen and nitrogen-containing compounds. *Bioresour. Technol.* **256**:160–169. DOI:10.1016/j.biortech.2018.02.016
 254. Seema H., Kemp K. C., Le N. H., et al. (2014). Highly selective CO₂ capture by S-doped microporous carbon materials. *Carbon* **66**:320–326. DOI:10.1016/j.carbon.2013.09.006
 255. Guo X., Zhang G., Wu C., et al. (2021). A cost-effective synthesis of heteroatom-doped porous carbon by sulfur-containing waste liquid treatment: As a promising adsorbent for CO₂ capture. *J. Environ. Chem. Eng.* **9**:105165. DOI:10.1016/j.jece.2021.105165
 256. Zhang X., Wu J., Yang H., et al. (2016). Preparation of nitrogen-doped microporous modified biochar by high temperature CO₂–NH₃ treatment for CO₂ adsorption: effects of temperature. *RSC Adv.* **6**:98157–98166. DOI:10.1039/c6ra23748g
 257. Zhang X., Zhang S., Yang H., et al. (2014). Nitrogen enriched biochar modified by high temperature CO₂–ammonia treatment: characterization and adsorption of CO₂. *Chem. Eng. J.* **257**:20–27. DOI:10.1016/j.cej.2014.07.024
 258. Liu S., Yang H., Su X., et al. (2019). Rational design of carbon-based metal-free catalysts for electrochemical carbon dioxide reduction: a review. *J. Energy Chem.* **36**:95–105. DOI:10.1016/j.jechem.2019.06.013
 259. Liu X. and Dai L. (2016). Carbon-based metal-free catalysts. *Nat. Rev. Mater.* **1**:1–12. DOI:10.1016/c2020-0-03378-5
 260. Daiyan R., Tan X., Chen R., et al. (2018). Electroreduction of CO₂ to CO on a mesoporous carbon catalyst with progressively removed nitrogen moieties. *ACS Energy Lett.* **3**:2292–2298. DOI:10.1021/acsenenergylett.8b01409
 261. Zhang S., Zhang X., Zhang S., et al. (2023). Biomass-derived functional carbon material for CO₂ adsorption and electrochemical CO₂ reduction reaction. *Carbon Capture Sci. Technol.* **9**:100135. DOI:10.1016/j.cscst.2023.100135
 262. Zhang S., Zhang X., Zhang J., et al. (2023). Three-dimension in-situ nitrogen doping porous cellulosic biomass-based carbon aerogel for electrocatalytic CO₂ reduction. *Fuel Process. Technol.* **242**:107612. DOI:10.1016/j.fuproc.2022.107612
 263. Hu X., Liu W. J., Ma L. L., et al. (2023). Sustainable conversion of harmful algae Biomass into a CO₂ reduction electrocatalyst for two-fold carbon utilization. *Environ. Sci. Technol.* **57**:1157–1166. DOI:10.1021/acs.est.2c07145
 264. Yao P., Qiu Y., Zhang T., et al. (2019). N-doped nanoporous carbon from biomass as a highly efficient electrocatalyst for the CO₂ reduction reaction. *ACS Sustain. Chem. Eng.* **7**:5249–5255. DOI:10.1021/acssuschemeng.8b06160
 265. Li F., Xue M., Knowles G. P., et al. (2017). Porous nitrogen-doped carbon derived from biomass for electrocatalytic reduction of CO₂ to CO. *Electrochim. Acta* **245**:561–568. DOI:10.1016/j.electacta.2017.05.174
 266. Hao X., An X., Patil A. M., et al. (2021). Biomass-derived N-doped carbon for efficient electrocatalytic CO₂ reduction to CO and Zn-CO₂ batteries. *ACS Appl. Mater. Interfaces* **13**:3738–3747. DOI:10.1021/acscami.0c13440
 267. Chen C., Sun X., Yan X., et al. (2020). Boosting CO₂ electroreduction on N, P-co-doped carbon aerogels. *Angew. Chem.* **132**:11216–11222. DOI:10.1002/ange.202004226
 268. Li S. and Tasnady D. (2023). Biochar for soil carbon sequestration: Current knowledge, mechanisms, and future perspectives. *C9*:67. DOI:10.3390/c9030067
 269. Li S. and Chan C. Y. (2022). Will Biochar Suppress or Stimulate Greenhouse Gas Emissions in Agricultural Fields. *Unveiling the Dice Game through Data Syntheses. Soil Syst.* **6**:73. DOI:10.3390/soilsystems6040073
 270. Vetter S. H., Abdalla M., Kuhnert M., et al. (2022). Soil carbon sequestration and biochar. *Greenh. Gas Remove. Technol.* **31**:194. DOI:10.1039/9781839165245-00194
 271. Weng Z., Van Zwieten L., Tavakkoli E., et al. (2022). Microspectroscopic visualization of how biochar lifts the soil organic carbon ceiling. *Nat. Commun.* **13**:5177. DOI:10.1038/s41467-022-32819-7
 272. Weng Z. H., Liu X., Eldridge S., et al. (2020). Priming of soil organic carbon induced by sugarcane residues and its biochar control the source of nitrogen for plant uptake: a dual 13C and 15N isotope three-source-partitioning study. *Soil Biol. Biochem.* **146**:107792. DOI:10.1016/j.soilbio.2020.107792
 273. Deng B., Yuan X., Siemann E., et al. (2021). Feedstock particle size and pyrolysis temperature regulate effects of biochar on soil nitrous oxide and carbon dioxide emissions. *Waste Manag.* **120**:33–40. DOI:10.1016/j.wasman.2020.11.015
 274. Singh N. and Kookana R. S. (2009). Organo-mineral interactions mask the true sorption potential of biochars in soils. *J. Environ. Sci. Health B* **44**:214–219. DOI:10.1080/03601230902728112
 275. Zhu Y., Yi B., Hu H., et al. (2020). The relationship of structure and organic matter adsorption characteristics by magnetic cattle manure biochar prepared at different pyrolysis temperatures. *J. Environ. Chem. Eng.* **8**:104112. DOI:10.1016/j.jece.2020.104112
 276. Ma S., Wang X., Wang S., et al. (2022). Effects of temperature on physicochemical properties of rice straw biochar and its passivation ability to Cu²⁺ in soil. *J. Soils Sediments* **22**:1418–1430. DOI:10.1007/s11368-022-03144-9
 277. Madiba O. F., Solaiman Z. M., Carson J. K., et al. (2016). Biochar increases availability and uptake of phosphorus to wheat under leaching conditions. *Biol. Fertil. Soils* **52**:439–446. DOI:10.1007/s00374-016-1099-3
 278. Lorenz K. and Lal R. (2014). Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *J. Plant Nutr. Soil Sci.* **177**:651–670. DOI:10.1007/jpln.2014.00058
 279. Wang L., O'Connor D., Rinklebe J. r., et al. (2020). Biochar aging: Mechanisms, physicochemical changes, assessment, and implications for field applications. *Environ. Sci. Technol.* **54**:14797–14814. DOI:10.1021/acs.est.0c04033

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AUTHOR CONTRIBUTIONS

Imran Zada conceived the idea and designed the review structure. Huyen Shen and Yanyu Li performed the literature research and analysis. Jiayan Luo and Shenmin Zhu contributed to drafting and revising the manuscript. Wendong Wei and Keryn Lian provided critical revisions and input on specific sections such as life cycle assessment: A holistic evaluation of sustainability and carbon capture storage and utilization. Yao Li and Di Zhang coordinated the writing and final editing of the manuscript. All authors contributed to the discussions, reviewed the manuscript, and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Not applicable.