Journal of Health, Education, Economics, Science, and Technology (J-HEST)
Volume 8 Nomor 2 Juni 2026 Hal. 183 - 200
e-ISSN:2685-1792

From Biomass to Functional Carbon Electrodes for Batteries and Supercapacitors: A Mini Review

Vinsensia Ade Sugiawati
Department of Chemical Analysis, Politeknik Negeri Ujung Pandang, Indonesia
Email: vinsensia.adesugiawati@poliupg.ac.id

ABSTRACT
The increasing global demand for high-performance energy storage systems has stimulated extensive research into the development of sustainable and efficient electrode materials. Conventional fossil-based and hazardous electrode materials often face limitations related to cost, environmental impact, resource availability, and long-term sustainability. In this context, biomass-derived carbon materials have emerged as promising alternatives due to their renewable origin, low cost, abundance, and environmentally benign nature. These materials can be engineered to possess tunable hierarchical porosity, large specific surface area, heteroatom doping, and tailored surface chemistry, which collectively improve ion transport, electrolyte wettability, charge storage behavior, and overall electrochemical performance. This review provides a comprehensive overview of biomass-derived carbon materials for next-generation supercapacitors and batteries, focusing on diverse biomass precursors, including agricultural residues, fruit and nut peels, woody biomass, and algae. Furthermore, the review highlights the structure–property–performance relationship of biomass-derived carbons and evaluates their potential in advanced energy storage applications.

Keywords*: Biomass, Energy Storage, Carbon Materials, Electrode.*

INTRODUCTION

The rapid growth of global energy consumption has intensified the demand for efficient and sustainable energy storage systems (Nasreldin et al., 2020). Renewable energy sources such as solar and wind have emerged as viable alternatives to fossil fuels, yet their intermittent nature makes energy generation dependent on reliable storage technologies. In response, the need for high-performance energy storage systems especially batteries and supercapacitors has emerged as the core target in contemporary energy research (Oh et al., 2025). Concurrently, conventional energy systems are increasingly being confronted with environmental issues leading to the transition towards greener and more sustainable materials. In this regard, the choice of the electrode materials is a critical factor to achieve performance and also the environmental influence of power-storage technology.

Carbon based materials such as graphite, activated carbon, carbon nanotubes (CNTs), and graphene have been extensively employed as electrode materials in lithium-ion batteries and supercapacitors (F. H. Hamid et al., 2025; S. Lee et al., 2026; G. Liu et al., 2025; J. Liu et al., 2026; Oh et al., 2025; Raza et al., 2026). One of the key advantages of carbon materials lies in their structural adaptability. Their widespread use is attributed to several intrinsic advantage, including tunable hierarchical porosity, large specific surface area, and excellent electrical conductivity. In addition, carbon materials can be engineered through heteroatom doping and tailored surface chemistry to further enhance electrochemical performance. Heteroatom doping refers to the intentional incorporation of non-carbon elements such as nitrogen, oxygen, sulfur, or phosphorus into the carbon lattice, which can modulate electronic structure, increase surface polarity, create additional active sites, and improve wettability toward electrolytes (F. H. Hamid et al., 2025; Merum & Kang, 2025). Despite these advantages, the conventional carbon materials face

sustainability limitations due to reliance on non-renewable of fossil-derived precursors and limited scalability associated with complex production routes and constrained supply chains. These factors collectively increase environmental impact, cost, and supply risk motivating the development of renewable and low-impact alternative carbon sources.

Biomass has emerged as a promising precursor for the production of sustainable carbon materials (F. H. Hamid et al., 2025; Oh et al., 2025). Derived from plant-based and biological sources, biomass is abundant, renewable, and widely available across different regions. Agricultural residues, forestry by-products, and even organic waste streams can serve as low-cost feedstocks for carbon material synthesis (figure 1). One of the most significant advantages of biomass is its intrinsic structural diversity. Natural biomass materials exhibit hierarchical architectures composed of micro-, meso-, and macropores, which can be partially preserved or further developed during carbonization and activation processes (Alemu & Assegie, 2026). This inherent porosity is highly beneficial for electrochemical applications, as it facilitates efficient ion transport and electrolyte accessibility (Z. Chen et al., 2020; Liang et al., 2022). The study aims to provide a systematic and comprehensive review of the biomass-to-carbon conversion pathway with specific focus on a structural, property, and performance-oriented aspects relevant to electrochemical energy storage applications.

METHOD

Carbonization Techniques

Carbonization is a thermochemical conversion step used to transform raw biomass into carbon-rich solid materials. Before the carbonization process, biomass is typically subjected to a pretreatment stage, which plays a crucial role in determining the quality of the final carbon product. Pretreatment may include physical size reduction (grinding and sieving), washing, chemical cleaning (acid or alkali treatment), and drying. These steps are aimed at removing impurities such as dust, inorganic minerals, surface contaminants, and excess moisture, while also improving feedstock homogeneity and enhancing subsequent thermal decomposition behavior. In some cases, chemical pretreatment using agents such as HCl, H_2SO_4, or NaOH is employed to remove metal ions and partially modify lignocellulosic structure, which can improve porosity development during carbonization.

During carbonization, biomass is then heated under oxygen-limited, inert, or sealed aqueous conditions so that dehydration, devolatilization, bond cleavage, and condensation reactions occur without complete combustion. The main purpose of carbonization is to remove moisture and volatile fractions while increasing the carbon content, aromaticity, and structural stability of the remaining solid (J. Liu et al., 2026; Reddy et al., 2026; Yan et al., 2024). For biomass-derived electrode materials, this step is essential because untreated biomass generally has low electrical conductivity, high oxygen/hydrogen content, and poor stability, whereas carbonized biomass provides a more suitable framework for further activation, doping, or direct electrochemical use. Recent reviews identify pyrolysis and hydrothermal carbonization as two of the most common routes for converting lignocellulosic biomass into carbon materials (figure 2).

Pyrolysis, also called direct carbonization, is the most widely used carbonization technique for biomass-derived carbon materials. It is commonly performed in nitrogen or argon atmosphere at moderate to high temperature, often around 400–900 °C, although the exact condition depends on feedstock composition and the desired carbon structure. During pyrolysis, hemicellulose, cellulose, and lignin decompose at different stages, releasing water, CO_2, CO, CH_4, tar, and other volatile compounds (Benigno et al., 2026). The remaining solid gradually becomes enriched in carbon through aromatization and condensation reactions. Higher pyrolysis temperature generally improves carbon ordering and electrical conductivity, but it may also reduce surface functional groups and carbon yield. Therefore, the final properties of pyrolyzed carbon are controlled by heating temperature, heating rate, residence time, gas atmosphere, and biomass composition.

Hydrothermal carbonization (HTC) is a lower-temperature carbonization route carried out in water inside a sealed reactor. Unlike dry pyrolysis, HTC can process wet biomass directly, which reduces the need for energy-intensive drying. Typical HTC conditions are commonly reported

around 180–250 °C under autogenous pressure, although broader temperature ranges have also been investigated depending on the material and target product (Alemu & Assegie, 2026; Oh et al., 2025). In this aqueous environment, biomass is converted into hydrochar through hydrolysis, dehydration, decarboxylation, polymerization, and aromatization reactions. HTC is particularly useful for biomass with high moisture content, such as algae, food waste, sludge, and agricultural residues. However, hydrochar usually has lower carbon ordering than high-temperature pyrolytic carbon, so additional heat treatment or activation is often required when high conductivity and advanced pore development are needed for energy-storage electrodes. Microwave-assisted carbonization is an alternative method that uses electromagnetic energy to heat biomass rapidly and more volumetrically than conventional external heating. In this process, microwave energy interacts with polar groups, moisture, inorganic species, or microwave absorbers within the biomass, generating heat from inside the material. This can shorten processing time, improve energy efficiency, and promote rapid formation of biochar or hydrochar depending on whether the process is conducted as microwave-assisted pyrolysis or microwave-assisted hydrothermal carbonization. Microwave treatment may also help tailor pore structure and surface chemistry, but the final product quality depends strongly on microwave power, residence time, absorber selection, reactor design, and feedstock dielectric properties. Scale-up remains more challenging than conventional furnace pyrolysis because uniform microwave penetration and reactor control are difficult at larger volumes. Thus, pyrolysis, hydrothermal carbonization, and microwave-assisted carbonization offer different advantages for preparing biomass-derived carbon materials (He et al., 2013; Pitchaikannu et al., 2025).

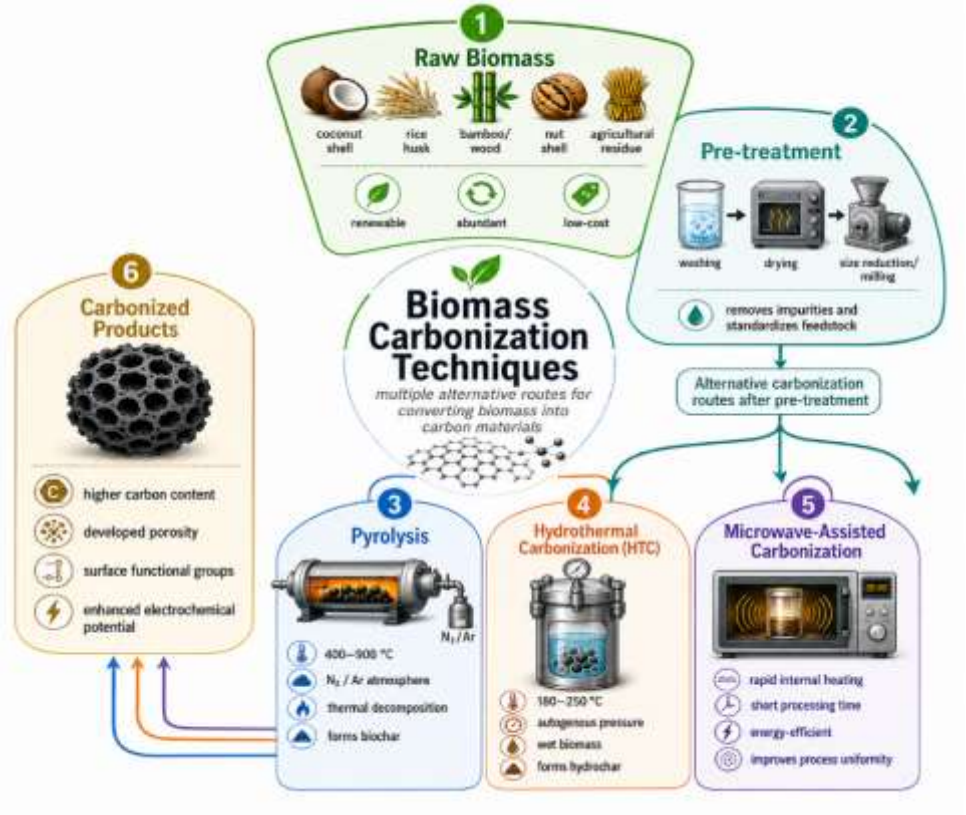

Figure 2. Schematic representation of biomass carbonization techniques

Activation Methods

Activation is a critical processing stage in the production of biomass-derived porous carbon because it enhances surface area, pore accessibility, and surface functionality. Carbonization forms the primary carbon framework, whereas activation further develops the pore network by opening blocked pores, generating new voids, and

regulating the distribution of micro-, meso-, and macropores. These structural changes are essential for applications such as adsorption, CO_2 capture, batteries, and supercapacitors, where ion diffusion, electrolyte penetration, and accessible active sites are strongly governed by the internal pore architecture (Wei, 2024).

Chemical activation is widely employed because it can produce highly porous carbon at relatively lower temperatures and shorter processing times than many physical activation routes. In this approach, the biomass precursor or pre-carbonized char is mixed with an activating reagent before thermal treatment. Common chemical activating agents include alkaline compounds such as KOH, NaOH, and K_2CO_3, Lewis acids such as $ZnCl_2$, and acids such as H_3PO_4 (M. Hamid et al., 2025; D. Liu et al., 2015; Ren et al., 2025; P. Saini et al., 2026; Surib et al., 2026). Depending on the activating agent, chemical activation can promote dehydration, devolatilization, carbon matrix etching, and pore formation.

The final texture of the carbon depends on several variables, including the activating agent, impregnation ratio, activation temperature and chemical composition of the biomass precursor. Among chemical activators, KOH is particularly effective for producing microporous carbon because reactions between KOH, oxygen-containing groups, and carbon fragments can etch the carbon framework and generate abundant vacancies and pores. At elevated temperatures, potassium-containing species may also penetrate and expand the carbon layers, improving internal accessibility. $ZnCl_2$ activation follows a different pathway (Benigno et al., 2026; X. Chen et al., 2017; He et al., 2013; Sun et al., 2026). $ZnCl_2$ acts mainly as a Lewis-acid/dehydrating agent that promotes biopolymer degradation, condensation, tar suppression, and porous framework formation, rather than functioning primarily through aggressive redox etching. This process can improve carbon yield and generate activated carbon with controlled pore structure, although the resulting porosity remains highly. H_3PO_4 activation is another important route for lignocellulosic biomass. It promotes dehydration, cross-linking, and the formation of thermally stable structures during thermal conversion (He et al., 2013; Hwang et al., 2008; Kong et al., 2024). This method is frequently associated with relatively high carbon yield and the formation of micro–mesoporous carbon, making it useful for applications requiring rapid ion transport and improved electrolyte accessibility. Its effectiveness is influenced by acid concentration, impregnation conditions, activation temperature, and the relative proportions of cellulose, hemicellulose, lignin, and ash in the feedstock.

Physical activation commonly uses oxidizing gases such as CO_2 or steam at high temperatures. During this process, the carbonized material reacts with CO_2 or water vapor to form gaseous products such as CO and H_2, gradually removing carbon atoms from the matrix and developing pores (Raza et al., 2026). Compared with chemical activation, physical activation avoids corrosive chemical reagents and reduces the need for intensive post-activation washing. However, it often requires higher temperatures and may produce lower surface areas than aggressive chemical activation, depending on the precursor, gasifying agent, temperature, and activation time.

Hybrid or physicochemical activation strategies combine the advantages of chemical and physical methods. A chemical activating agent may first be used to generate initial porosity, followed by CO_2 or steam treatment to widen pores and improve interconnection between pore channels. This approach is useful for producing hierarchical carbon structures, in which micropores contribute to charge storage or adsorption capacity, while mesopores and macropores facilitate mass transfer. Recent studies confirm that hybrid chemical–physical activation is effective for biomass-derived supercapacitor carbons. Yılmaz et al. used pistachio shells and combined KOH chemical activation with CO_2 physical activation, producing hierarchical micro/meso/macroporous carbon with a surface area of 1318.4 $m^2\ g^{-1}$ and a specific capacitance of 151 F g^{-1} at 0.5 A g^{-1}; the electrode also retained good cycling stability, with only 8.6% capacitance loss after 500 cycles (Yılmaz et al., 2023). A similar approach was reported for date seed biomass, where KOH activation combined with CO_2 treatment produced a hierarchical nanofiber-like carbon framework with interconnected pores; the optimized electrode

delivered 258.88 F g^{-1} at 1 A g^{-1}, with an energy density of 7.11 Wh kg^{-1} and power density of 125.46 W kg^{-1} (Farma et al., 2023). Such multiscale pore architecture is especially desirable for supercapacitor electrodes and other electrochemical systems that require both high surface area and rapid ion movement. Schematic representation of activation methods for converting biomass into activated carbon are illustrated in figure 3.

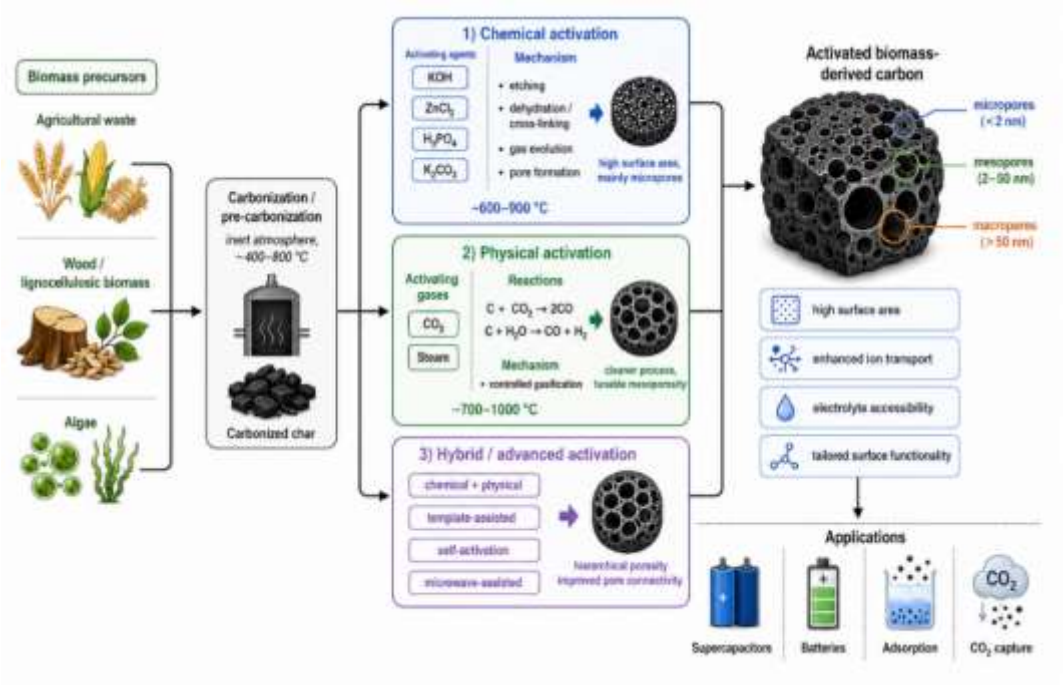

Figure 3. Schematic representation of activation methods for converting biomass into activated carbon

RESULTS AND DISCUSSION

Types Of Biomass

Coconut Shell

Coconut shell is widely recognized as one of the most effective biomass precursors for the production of high-performance carbon materials due to its unique chemical composition, dense morphology, and high lignin content**.** Coconut shell can be converted into porous activated carbon or hard carbon through carbonization, pyrolysis, steam activation, KOH/$ZnCl_2$ activation, hydrothermal treatment, or combined activation routes (Technology et al., 2025). For supercapacitors, coconut-shell-derived activated carbon is especially attractive because its micro/mesoporous structure provides a large surface area for electric-double-layer charge storage. Mi et al. prepared coconut-shell porous carbon with tunable micro/mesopore ratio and reported that higher mesoporosity reduced equivalent series resistance and improved capacitance retention at high current density. In supercapacitor applications, the main role of coconut-shell carbon is to provide ion-accessible pores, stable carbon frameworks, and good electrochemical reversibility (Mi et al., 2012). Barzegar et al. reported coconut-shell activated carbon electrodes with a specific capacitance of 186 F g^{-1}, energy density of about 11 Wh kg^{-1}, and stable cycling up to 10,000 cycles in a polymer gel electrolyte (Barzegar et al., 2016). Lee et al. further showed that coconut-shell activated carbon can be used in solid-state supercapacitors, with high capacitance and good cycling retention, demonstrating that this biomass can be applied not only in liquid-electrolyte cells but also in safer, flexible, or portable solid-state devices (K. C. Lee et al., 2021).

For batteries, coconut shell is more commonly investigated as a hard-carbon anode rather than as ordinary activated carbon, because hard carbon contains disordered graphitic domains, enlarged

interlayer spacing, and closed nanopores that can store Li^+, Na^+, or K^+ ions. Early work by Hwang et al. showed that disordered carbons obtained from coconut shells could be used as anode materials for lithium batteries (Hwang et al., 2008). For sodium-ion batteries, Nita et al. compared hard carbons from coconut shells, walnut shells, and corn silk, showing that biomass composition, ash content, surface oxygen groups, and structural ordering strongly influence initial Coulombic efficiency and reversible capacity (Nita et al., 2021). More recent studies improved coconut-shell hard carbon through N/O codoping, ball milling, alkali activation, and pore-structure regulation to enhance sodium storage capacity and initial Coulombic efficiency (P. Saini et al., 2026).

Biomass-derived carbons typically exhibit moderate to low ICE values, generally in the range of ~50–85%, depending on precursor type, porosity, and activation strategy (Hwang et al., 2008; L. Wang et al., 2013). This limitation is mainly attributed to extensive solid electrolyte interphase (SEI) formation and irreversible lithium/sodium ion trapping within high-surface-area porous structures. Materials such as rice husk-derived carbon and coconut shell-based hard carbon have been reported to show ICE values around 60–80%, where the relatively higher defect density and surface functional groups promote increased electrolyte decomposition during the first cycle (Misnon et al., 2018) . The relatively low ICE observed in biomass-derived carbons is strongly correlated with their structural characteristics, particularly high specific surface area, abundant oxygen-containing functional groups, and disordered carbon frameworks, all of which intensify irreversible side reactions (Sugiawati et al., 2020). In contrast, more graphitized or less porous carbon structures tend to exhibit improved ICE due to reduced interfacial reactivity and suppressed SEI growth. Recent studies also demonstrate that ICE can be significantly improved through structural engineering approaches such as heteroatom doping, pore size optimization, and controlled carbonization, which help stabilize the electrode–electrolyte interface and reduce irreversible ion loss (Benigno et al., 2026; Ren et al., 2025). Overall, coconut shell is a versatile precursor for both supercapacitor-type electrodes and battery-type anodes. The future development should focus on controlled carbonization temperature, impurity removal, pore-size optimization, heteroatom doping, and scalable green activation methods.

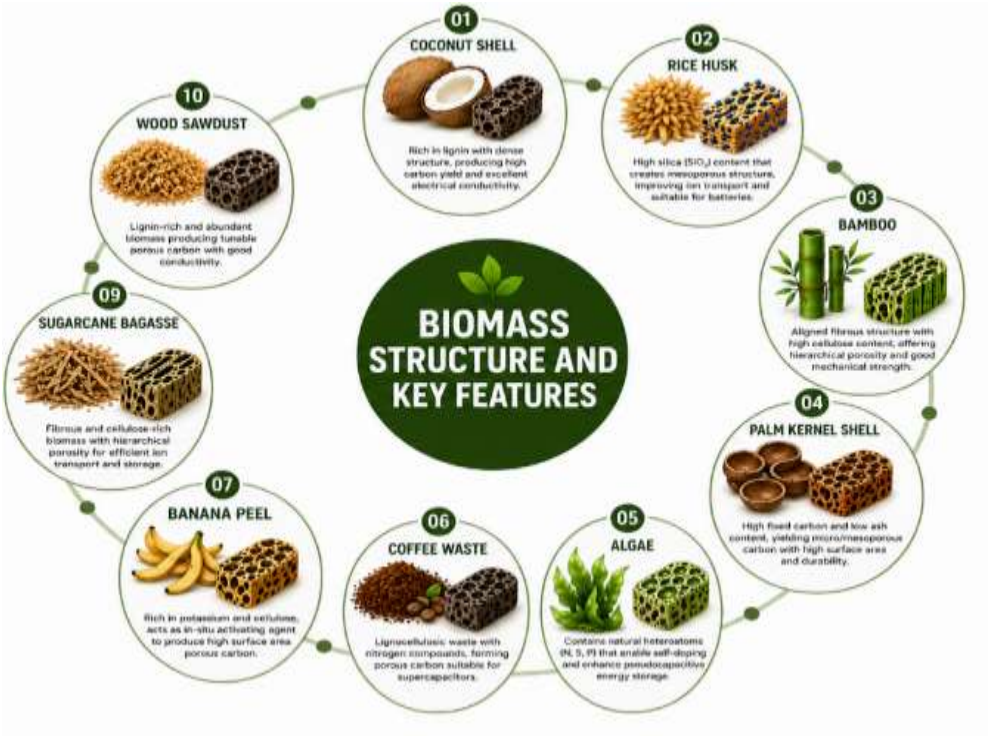

Figure 1. Schematic representation of various biomass precursors and their key structural features relevant to energy storage applications.

Rice Husk

Rice husk is an attractive biomass precursor for electrochemical energy-storage electrodes because it contains organic carbon sources together with naturally embedded silica. During carbonization, activation, acid/alkali leaching, or pyrolysis, these components can be converted into porous carbon, carbon–silica composites, SiOx/C composites, or hard carbon. The silica phase can act as an internal template, while cellulose, hemicellulose, and lignin generate the carbon framework. Therefore, rice husk is useful not only for low-cost porous carbon electrodes in supercapacitors but also for battery anodes where disordered carbon, SiOx, and heteroatom-doped carbon can contribute to ion storage (J. Liu et al., 2026).

For supercapacitors, rice-husk-derived carbon is mainly used as an electric-double-layer capacitor electrode. Its performance depends strongly on surface area, pore-size distribution, oxygen-containing functional groups, and electrolyte-accessible channels. Liu et al. prepared hierarchical porous carbon from rice husk by carbonization, NaOH leaching, and KOH activation; the material reached a high surface area of 2804 $m^2\ g^{-1}$ and showed 278 F g^{-1} at 0.5 A g^{-1} in 6 M KOH. The study emphasized that rice husk silica plays an important self-template role in forming macrochannels, mesopores, and micropores (D. Liu et al., 2015). He et al. also reported rice-husk-derived porous carbon prepared by $ZnCl_2$ activation for high-capacitance supercapacitors, showing that chemical activation can greatly enhance porosity and capacitance (He et al., 2013).

For lithium-ion batteries, rice husk can be converted into porous carbon, hard carbon, or SiOx/C-type anode materials. Wang, Schnepp, and Titirici obtained carbon fibers from rice husk using hydrothermal carbonization followed by heat treatment at 1000 °C; removal of silica increased porosity, and the resulting carbon showed good capacity retention and rate performance as a lithium-ion battery anode [19]. Phosphorus doping has also been used to improve lithium storage: Wang et al. reported phosphorus-doped porous carbon from rice husk with 757 mAh g^{-1} after 100 cycles at 100 mA g^{-1} and 382 mAh g^{-1} at 2000 mA g^{-1}, attributed to the combination of 3D interconnected porosity and phosphorus-induced electrochemical activity [26]. In addition, SiOx/C composites from rice husk are important because silicon oxide can provide high lithium-storage capacity, although volume expansion and cycling stability must be controlled. For sodium-ion and potassium-ion batteries, rice-husk-derived hard carbon is especially promising because its disordered carbon layers, nanopores, and enlarged interlayer distance can accommodate larger Na^+ or K^+ ions better than graphite. Rybarczyk et al. also prepared rice-husk hard carbon through a single pyrolysis process and showed that treatment temperature affected morphology, graphitization degree, and nanovoid formation [27]. Overall, rice husk is a highly versatile waste-derived precursor, but future research should focus on reproducible ash/silica control, green activation, improved initial Coulombic efficiency, and full-cell fabrication.

Bamboo

Bamboo is a suitable biomass precursor for energy-storage electrodes because it is renewable, fast-growing, lignocellulose-rich, and naturally forms carbon frameworks after carbonization. Its cellulose, hemicellulose, and lignin can be converted into porous carbon, activated carbon, nitrogen-doped carbon, hard carbon, or Si/C-type composites depending on the treatment method. Common preparation routes include hydrothermal pretreatment, direct pyrolysis, KOH/NaOH activation, $ZnCl_2$ activation, ball milling, acid washing, and high-temperature carbonization [28]. The resulting bamboo-derived carbons are attractive for supercapacitors because they can provide high surface area and hierarchical pores, while for batteries they can provide disordered carbon layers, defects, interlayer spacing, and closed pores for ion storage.

For supercapacitors, bamboo-derived porous carbon mainly works through electric-double-layer capacitance, while nitrogen or oxygen functional groups may add pseudocapacitive contribution and improve electrolyte wettability. Chen et al.

prepared hierarchical nitrogen-doped carbon from bamboo shoot by hydrothermal treatment and carbonization without additional chemical activation or nitrogen source; the best sample showed 412 F g^{-1} at 0.9 A g^{-1}, 270 F g^{-1} at 5 A g^{-1}, and 99.5% capacitance retention after 5000 cycles [29]. Qiu et al. further showed that the cellulose, hemicellulose, and lignin fractions of bamboo shavings influence the pore structure and electrochemical properties of bamboo-based hierarchical porous carbon (Qiu et al., 2022). These results indicate that bamboo is not only a carbon source but also a structurally useful precursor for designing ion-accessible porous electrodes.

For lithium-ion batteries, bamboo can be converted into carbonaceous anodes or silicon/carbon composites, especially when bamboo leaves or bamboo charcoal are used as silica- or carbon-containing precursors. Zhao et al. investigated carbon derived from bamboo shoot as a lithium-ion battery anode, showing that direct carbonization of bamboo biomass can produce active carbon materials for Li^+ storage (Zhengping Zhao et al., 2020). Another important route is the preparation of silicon-based composites from bamboo leaves. For sodium-ion batteries, bamboo-derived hard carbon is especially promising because hard carbon can store Na^+ through adsorption at defects, intercalation between disordered carbon layers, and filling in closed nanopores. Gao et al. prepared bamboo-waste-derived hard carbon using a two-step carbonization process; the optimized HCB-1400 delivered 328.4 mAh g^{-1} at 30 mA g^{-1} and the full cell showed 249.25 Wh kg^{-1} with 93% capacity retention after 200 cycles (Gao et al., 2024). Overall, bamboo is a strong biomass candidate for both supercapacitors and batteries, but future studies should improve reproducibility, ash/impurity removal, green activation, initial Coulombic efficiency, and full-cell fabrication.

Palm Kernel Shell

Palm kernel shell (PKS) is a strong biomass precursor for electrochemical energy-storage electrodes because it is abundant, low-cost, non-edible, carbon-rich, and generated in large quantities from the palm-oil industry. Its rigid lignocellulosic structure can be converted into activated carbon, porous carbon, carbon fiber, reduced graphene oxide, or hard carbon through pyrolysis, carbonization, KOH activation, H_3PO_4 activation, steam activation, electrospinning, and heteroatom-regulation routes (Kongthong et al., 2023). For electrode applications, the main advantages of PKS-derived carbon are its tunable porosity, relatively high fixed carbon content after thermal treatment, good chemical stability, and ability to form micro/mesoporous networks that support electrolyte-ion transport.

For supercapacitors, Misnon et al. prepared activated carbon from oil palm kernel shell using pyrolysis followed by physical or chemical activation; the chemically activated carbon showed wider pore distribution, about 210 F g^{-1} at 0.5 A g^{-1} in 1 M KOH, and 95–97% capacitance retention after 1000 cycles (Misnon et al., 2018). More recent work by Li et al. produced O/P/S self-doped hierarchical porous carbon from PKS; the optimized material reached 2521 m^2 g^{-1} and 360 F g^{-1}, showing that pore engineering and self-doping are effective strategies for high-performance (Li et al., 2023).

For batteries, PKS-derived carbon is especially relevant as a hard-carbon-type anode for dual-carbon batteries and sodium-ion batteries. Kongthong et al. used palm-kernel-shell-derived hard carbon as the anode in a quasi-solid-state lithium-ion dual-carbon battery; the KOH-activated hard carbon had a large surface area of 1843 m^2 g^{-1}, and the assembled device delivered 73.6 mAh g^{-1} over 500 cycles (Kongthong et al., 2023). Ren et al. recently used PKS as a representative biomass precursor for sodium-ion hard carbon and achieved 410.2 mAh g^{-1} reversible capacity, 94.6% initial Coulombic efficiency, and 95.4% capacity retention after 1000 cycles at 10 C by regulating closed pores and ultra-micropore defects (Ren et al., 2025) . To conclude, PKS is a versatile waste-derived electrode precursor, but future studies should focus on reproducible activation, ash/mineral control, lower chemical consumption, improved initial Coulombic efficiency, and full-cell fabrication for practical battery and supercapacitor systems.

Algae

Algae, including microalgae, macroalgae/seaweed, and diatoms, are promising biomass precursors for sustainable electrodes because they contain

carbon-rich biopolymers, natural heteroatoms, and inorganic components that can be converted into porous carbon, doped carbon, hard carbon, SiO_2/C composites, or carbon–metal compound composites. Compared with many terrestrial biomass sources, algae often contain naturally occurring N, O, S, P, and mineral salts, which can help form self-doped carbon frameworks after pyrolysis, hydrothermal carbonization, activation, or carbon coating. A recent review emphasized that algae-derived carbon materials are being explored for supercapacitors, batteries, graphene-related materials, and other energy-storage applications because of their scalable and sustainable origin (Zhu et al., 2018).

For supercapacitors, algae-derived carbon mainly functions through electric-double-layer capacitance, supported by high surface area, hierarchical pores, and electrolyte-accessible channels. For lithium-ion batteries, algae-derived carbons can act as anodes because their disordered carbon structure, defects, heteroatom doping, and porous networks provide sites for Li^+ storage and shorten ion-diffusion pathways. Yu et al. reported algae-derived N,O-codoped carbon anodes with high lithium-storage capacity of 1347–1709 mAh g^{-1} and cycling stability up to 500 cycles (Yu et al., 2016). For sodium-ion batteries, algae-derived hard carbon is especially important because Na^+ is larger than Li^+ and requires disordered carbon layers, defects, open/closed pores, and suitable interlayer spacing. Gibertini et al. used *Chlorella vulgaris* algae pyrolyzed at 800–1100 °C to produce non-graphitic hard carbon anodes for Na-ion batteries, confirming that pyrolysis temperature controls structure and electrochemical performance (Gibertini et al., 2021). Algae-derived electrodes are promising for both batteries and supercapacitors, but future work should focus on ash/mineral control, acid-washing optimization, reproducible feedstock composition, green activation, full-cell testing, and scale-up (Ge et al., 2021; Zhu et al., 2018). To compare, the performances of biomass-derived carbon electrodes for batteries and supercapacitors, as shown in table 1.

Table 1 summarizes biomass-derived carbon electrode materials used for electrochemical energy storage, including their sources, synthesis routes, and reported electrochemical performances. The results indicate that biomass precursors such as rice husk, banana peel, algae, and coconut shell can be effectively converted into porous carbon structures with promising electrochemical properties for both supercapacitor and battery applications. Among the reported materials, activation and heteroatom doping significantly enhance electrochemical performance by increasing surface area, improving ion diffusion pathways, and introducing additional active sites. For instance, N-doped porous carbon derived from algae demonstrates high specific capacitance and excellent cycling stability, indicating the role of nitrogen functional groups in improving charge storage behavior. In addition, chemically activated carbons such as KOH-activated coconut shell and $ZnCl_2$-activated spent coffee grounds exhibit improved energy density and capacity retention, highlighting the importance of activation strategy in tailoring pore structure. However, performance comparison across studies remains challenging due to differences in testing conditions, including current density, electrolyte type, and cycle number. Furthermore, although several studies report high initial capacity or capacitance, long-term stability and coulombic efficiency are not always consistently evaluated, which limits direct assessment of practical applicability. Therefore, future studies should adopt standardized electrochemical testing protocols and report ICE (initial coulombic efficiency) to better evaluate real-world feasibility.

Table 1. Biomass-Derived Carbon Electrode Materials for Electrochemical Energy Storage Devices

Biomass Source	Derived Electrode Material	Application	Reported Performance	Ref.
Rice husk	Hierarchical porous carbon	Supercapacitor	At the current density of 0.5 A g_1, the RHPC, PC1, PC2, and PC3 electrodes deliver specific capacitances of 256, 192, 263, and 205 F g_1, respectively	(Z. Chen et al., 2020)
Banana peel	Porous carbon	Li-ion battery anode	272 mAh/g after 200 cycles at 0.2 C	(Luna-Lama et al., 2021)
Algae	N-self doped porous carbon	Supercapacitor	specific capacitance of 353 F g^{-1} at 1 A g^{-1} and 92% capacitance retention after 10 000 charge–discharge cycles at 20 A g^{-1}	(Zhu et al., 2018)
Palm kernel shell	Palm-kernel-shell-derived hard carbon	Supercapacitor	The highest energy density was obtained in Na_2SO_4 electrolyte (7.4 Wh kg^{-1}) at a power density of 300 W kg^{-1}. The device stability cycle at low current density (0.5 A g^{-1}) for 3500 times showed capacitance retention in range of 78–114% in all devices.	(Misnon et al., 2018)
Bamboo waste	Bamboo-waste-derived hard carbon, HCB-1400	Sodium-ion battery anode	Reversible capacity of 328.4 mAh **g^{-1}** at 30 mA g^{-1}	(Gao et al., 2024)
Corncob waste	Corncob-derived hard carbon electrode with CMC binder	Sodium-ion battery anode	Around 264 mAh g^{-1} at 1 C; 84% retention after 100 cycles.	(Bottoni et al., 2023)
Coconut shell	KOH-activated coconut-shell carbon	Solid-state symmetric supercapacitor	449 F g^{-1} at 1 A g^{-1}; device energy density 48.9 Wh kg^{-1}; 92% retention after 5000 cycles.	(K. C. Lee et al., 2021)
Spent coffee grounds	$ZnCl_2$-activated hybrid carbon with Zn-based oxides	Li-ion battery anode	Optimized HCs_2 electrode delivered 692 mAh g^{-1} after 100 cycles.	(Vo et al., 2024)
Peanut shell	Peanut-shell-based hard carbon	Sodium-ion battery anode	Reversible sodium storage capacity up to 357.55 mAh g^{-1}**;** first Coulombic efficiency 63.4% at 30 mA g^{-1}.	(Jia et al., 2025)
Orange peel	KOH-activated orange-peel-derived hard carbon	Li-ion / Na-ion battery anode	LIB initial capacity 878 mAh g^{-1} at 1 A g^{-1}; NIB initial capacity 497 mAh g^{-1} at 0.5 A g^{-1}.	(Xiang et al., 2017)
Rice husk	C/SiO_x composite carbon	Li-ion battery anode	C and SiO_x specific capacities reported as 375 and 475 mAh g^{-1}**;** stable operation achieved by pre-lithiation	(Abe et al., 2022)

Additional Biomass Waste Precursors

While the previous sections discuss selected biomass precursors individually, this section

combines several alternative biomass waste precursors. Additional biomass waste precursors such as banana peel, orange peel, spent coffee grounds, sugarcane bagasse, corn cob, sawdust, peanut shell, walnut shell, and paper waste are increasingly studied as sustainable carbon sources for electrochemical energy-storage electrodes. These wastes contain cellulose, hemicellulose, lignin, starch, protein, natural minerals, and heteroatoms that can be transformed into porous carbon, activated carbon, hard carbon, heteroatom-doped carbon, or carbon/composite electrodes. In supercapacitors, these materials are mainly designed to provide high surface area, hierarchical pores, and electrolyte-accessible channels, while in batteries they are usually engineered into hard carbon or carbon–metal oxide composites to support Li^+, Na^+, or K^+ storage. Biomass-derived carbon is attractive because it is low-cost, widely available, environmentally friendly, and structurally tunable through carbonization, hydrothermal treatment, KOH activation, H_3PO_4 activation, $ZnCl_2$ activation, and heteroatom doping.

Fruit and beverage wastes are among the most useful additional precursors. Banana peel has a naturally porous structure and can be converted into activated carbon for supercapacitors or into carbon-based hybrid electrodes for batteries. Activated banana-peel-derived materials for both supercapacitors and Li–S batteries, where the porous banana-peel carbon supported Ni/graphene structures and improved electrochemical performance. Tripathy et al. also showed that banana-peel-derived activated carbon delivered 227 F g^{-1} at 1 A g^{-1} with about 97% capacitance retention after 5000 cycles (Tripathy et al., 2021). Spent coffee grounds are also promising because they naturally contain nitrogen; Sangprasert et al. produced N-containing activated carbon from spent coffee grounds with 1835 m^2 g^{-1} surface area, 312 F g^{-1} capacitance, and 592 mAh g^{-1} as a lithium-ion battery anode (Sangprasert et al., 2022). Orange peel is more often used for hard-carbon anodes, and studies have reported orange-peel-derived hard carbon for Li-ion and Na-ion battery applications.

Agricultural and wood-based residues such as sugarcane bagasse, corn cob, and sawdust are also important electrode precursors. Sugarcane bagasse has been converted into porous carbon for supercapacitors, MnO_2/bagasse-derived carbon composites for lithium-ion batteries, and hard carbon for potassium-ion storage. Nut shells and other hard agricultural wastes are especially suitable for hard-carbon battery anodes because their dense lignocellulosic structure favors disordered carbon layers, expanded interlayer spacing, and closed-pore formation after high temperature carbonization. Peanut shell is another strong candidate; Jia et al. prepared peanut-shell-based hard carbon with 357.55 mAh g^{-1} reversible sodium-storage capacity, although the initial Coulombic efficiency still required improvement (Jia et al., 2025). These additionalbiomass wastes broaden the choice of low-cost electrode precursors. For supercapacitors, the most important target is high accessible surface area with balanced micro/mesopores, while for batteries the key challenge is controlling defects, interlayer spacing, closed pores, ash content, and initial Coulombic efficiency. Comparison of energy storage using biomass-derived carbon can be seen in Table 2.

Table 2 compares the application of biomass-derived carbon materials in different electrochemical energy storage systems, including supercapacitors, lithium-ion batteries, sodium-ion batteries, potassium-ion batteries, and lithium–sulfur batteries. The comparison shows that biomass-derived carbons can serve different electrochemical functions depending on the storage mechanism of each system. In supercapacitors, porous and heteroatom-doped carbons mainly contribute to electric double-layer capacitance and pseudocapacitance, where high surface area, accessible pores, and surface functional groups play a crucial role in improving capacitance and cycling stability. For battery systems, the function of biomass-derived carbon becomes more diverse, including ion insertion, adsorption, intercalation, surface storage, conductivity enhancement, and structural buffering.

Table 2. Comparison of Energy Storage Systems Using Biomass-Derived Carbon Materials

Energy Storage System	Biomass-derived carbon role/material	Main charge-storage mechanism	Representative performance reported in literature	Ref.
Supercapacitors	Activated porous carbon, hierarchical porous carbon, heteroatom-doped carbon	Electric double-layer capacitance; some pseudocapacitance from N/O/S/P functional groups	orange-peel activated carbon reaching 460 F g^{-1} with 98% retention after 10,000 cycles.	(S. Saini et al., 2021)
Lithium-ion batteries, LIBs	Porous carbon, hard carbon, carbon nanosheets/fibers, carbon coatings, carbon–Si or carbon–metal oxide composites	Li^+ insertion/adsorption, surface storage, conversion/alloying support in composites	Biomass-derived carbon materials for LIBs often exceed 500 mAh g^{-1}, and some composites exceed 1,000 mAh g^{-1}	(Lin et al., 2024)
Sodium-ion batteries, SIBs	Biomass-derived hard carbon anodes from lignocellulosic waste, shells, fibers, agricultural residues	Na^+ adsorption in defects/pores and insertion into turbostratic carbon layers	Reported capacities 203.6 mAh g^{-1} from peanut-shell hard carbon and 358 mAh g^{-1} from Borassus flabellifer-derived hard carbon	(Yan et al., 2024)
Potassium-ion batteries, PIBs	Biomass-derived hard/porous carbon anodes, often activated or heteroatom-doped	K^+ adsorption/intercalation with pseudocapacitive contribution	Recent lignin-derived hard carbons showed strong cycling stability, including 88.8% capacity retention after 500 cycles in one study.	(Benigno et al., 2026)
Lithium–sulfur batteries, Li–S	Porous/doped biomass carbon as sulfur host, interlayer, conductive scaffold, or polysulfide-trapping matrix	Sulfur redox conversion; carbon improves conductivity and suppresses polysulfide shuttle	Biomass-derived porous carbons are widely studied as sulfur hosts; marine-waste-derived carbons showed promising capacity retention over 500 cycles in Li–S cells.	(Zhiqiang Zhao et al., 2022)

Among the compared systems, lithium-ion batteries generally show high reversible capacities when biomass-derived carbon is combined with nanosheets, fibers, coatings, or carbon–Si/metal oxide composites. However, direct comparison among studies remains difficult because the reported values are often obtained under different current densities, voltage windows, electrode loadings, and cycle numbers. In sodium- and potassium-ion batteries, biomass-derived hard carbon is particularly important because its turbostratic structure, defect sites, and microporous domains can facilitate Na^+ or K^+ storage. Nevertheless, these systems still face challenges related to initial Coulombic efficiency, sluggish ion diffusion, and long-term structural stability.

For lithium–sulfur batteries, biomass-derived porous carbon is mainly used as a sulfur host, conductive scaffold, and polysulfide-trapping matrix. Its porous structure can accommodate sulfur species, improve electrical conductivity, and suppress the shuttle effect. Overall, the data indicate that biomass-derived carbon materials are versatile electrode components for multiple energy storage systems. Future studies should report standardized electrochemical parameters, including specific capacity or capacitance, current density, cycling number, capacity retention, and initial Coulombic efficiency, to enable a more reliable comparison of their practical potential.

Challenges, Limitations, And Future Perspectives

Carbon materials generated from biomass have drawn considerable attention in applications of energy storage due to their renewable nature, relatively low cost, low density, tunable structure, and promising electrochemical performance. But there are few hurdles to overcome before these materials are applied to many practical devices. A big obstacle is the inherent heterogeneity of biomass feedstocks. For each particular biomass source, growing conditions, harvesting times and processing history will shape the cellulose, hemicellulose, lignin, ash and inorganic minerals ratio and its percentage.

Numerous lab-scale techniques resulted in high-performance carbons from biomass, but the adaptation of the methods for applications in industry is still challenging. This results in controlled temperature, heating rate, atmosphere, time, and chemical formulation for massive synthesis operations. Unlike small laboratory runs, these parameters are more challenging in industrial reactors to establish in perfect uniformity. This means that processes which are effective at the lab scale will become less efficient, more expensive, or less reproducible when scaled up.

Environmental and production costs are also two major issues. Even though biomass is renewable in nature, transformation to functional carbon materials frequently requires high-temperature treatment and chemical activation, potentially negating its benefits for sustainability. Activating agents including KOH and $ZnCl_2$ are corrosive and produce waste streams requiring in-depth washing, filtration, drying, neutralizing, and disposing processes. Post-treatment processes consume more water, require more chemicals, consume more energy, and result in higher operational costs. Therefore greener, more cost-effective activation strategies are required to increase the overall development sustainability of carbon production from biomass (S. Saini et al., 2021).

Future research will focus on designing greener, energy efficient and economical catalysts. Promising avenues are bio-derived activating agents, self-activation, salt-assisted activation, lower-temperature treatment, reagent recovery and life-cycle assessment-guided process optimization. Advances in artificial intelligence and machine learning could also aid in accelerated material engineering process with respect to assessing the associations between biomass composition, synthesis parameters, pore structure, surface chemistry, and electrochemical activity. Furthermore, for flexible and wearable energy storage devices, and hybrid battery–supercapacitor systems that combine high energy density, high power density, and long cycle life while providing sustainability, biomass-based carbons are also of increasing importance.

CONCLUSION

Biomass-derived carbon can be produced from various agricultural and biological wastes through several key stages, including pretreatment, carbonization, and activation. Pretreatment improves feedstock uniformity, while carbonization converts raw biomass into carbon-rich materials such as biochar, hydrochar, or carbonized biomass by removing moisture, volatile compounds, and oxygen- or hydrogen-containing groups. Activation further enhances the material by increasing surface area, forming micro/mesopores, improving conductivity, and creating more accessible active sites. Physical, chemical, and combined activation methods offer different advantages, depending on the desired properties and final application. Therefore, optimized biomass-derived activated carbon is a promising functional electrode material for supercapacitors and batteries.

REFERENCES

Abe, Y., Tomioka, M., Kabir, M., & Kumagai, S. (2022). Role of SiOx in rice-husk-derived anodes for Li-ion batteries. *Scientific Reports*, *12*(1), 975. https://doi.org/10.1038/S41598-022-04979-5

Alemu, M. A., & Assegie, A. A. (2026). Recent advancements in biomass-origin carbon structures for next-generation supercapacitors. *IScience*, *29*(3), 114865. https://doi.org/10.1016/J.ISCI.2026.114865

Barzegar, F., Khaleed, A. A., Ugbo, F. U., Oyeniran, K. O., Momodu, D. Y., Bello, A., Dangbegnon, J. K., & Manyala, N. I. (2016). *Cycling and floating performance of symmetric supercapacitor derived from coconut shell biomass*. https://doi.org/10.1063/1.4967348

Benigno, A., Raviolo, S., Trano, S., Domenici, S., Castellino, M., Francia, C., Gaspar, D., Pereira, L., & Bella, F. (2026). From biomass to battery: lignin-derived carbons achieving unprecedented high capacity retention in potassium batteries. *Chemical Engineering Journal*, *528*, 172142. https://doi.org/10.1016/J.CEJ.2025.172142

Bottoni, L., Darjazi, H., Sbrascini, L., Staffolani, A., Gabrielli, S., Pastore, G., Tombesi, A., & Nobili, F. (2023). Electrochemical Characterization of Charge Storage at Anodes for Sodium-Ion Batteries Based on Corncob Waste-Derived Hard Carbon and Binder. *ChemElectroChem*, *10*(8), e202201117. https://doi.org/10.1002/CELC.202201117;CTYPE:STRING:JOURNAL

Chen, X., Zhang, J., Zhang, B., Dong, S., Guo, X., Mu, X., & Fei, B. (2017). A novel hierarchical porous nitrogen-doped carbon derived from bamboo shoot for high performance supercapacitor. *Scientific Reports 2017 7:1*, *7*(1), 7362-. https://doi.org/10.1038/s41598-017-06730-x

Chen, Z., Wang, X., Xue, B., Li, W., Ding, Z., Yang, X., Qiu, J., & Wang, Z. (2020). Rice husk-based hierarchical porous carbon for high performance supercapacitors: The structure-performance relationship. *Carbon*, *161*, 432–444. https://doi.org/10.1016/J.CARBON.2020.01.088

Farma, R., Nur'aini, N., Apriyani, I., Awitdrus, A., Taer, E., & Apriwandi, A. (2023). Honeycomb-Like Carbon with Tunable Pore Size from Biomass Phoenix Dactylifera Midrib for Highly Compressible Binder-Free Supercapacitors. *JOM: The Journal of The Minerals, Metals & Materials Society (TMS)*, *75*(3), 708. https://doi.org/10.1007/S11837-022-05667-5

Gao, T., Zhou, Y., Jiang, Y., Xue, Z., & Ding, Y. (2024). Bamboo waste derived hard carbon as high performance anode for sodium-ion batteries. *Diamond and Related Materials*, *150*, 111737. https://doi.org/10.1016/J.DIAMOND.2024.111737

Ge, L., Wu, Y., Wang, F., & Huang, Y. (2021). Algae-Derived Nitrogen Self-Doped Porous Carbon Materials with High Supercapacitor Performances. *Energy & Fuels*, *35*(18), 15118–15125. https://doi.org/10.1021/ACS.ENERGYFUELS.1C01827

Gibertini, E., Liberale, F., Dossi, C., Binda, G., Mattioli, B., Bettinetti, R., Maspero, A., Fiore, M., Ruffo, R., & Magagnin, L. (2021). Algae-derived hard carbon anodes for Na-ion batteries. *Journal of Applied Electrochemistry 2021 51:12*, *51*(12), 1665–1673. https://doi.org/10.1007/S10800-021-01609-2

Hamid, F. H., Yunita, K. S., Mashuni, M., & Jahiding, M. (2025). *A Review on Carbon Materials Derived from Biomass Pyrolysis for Supercapacitor Applications*. *April*, 53–70.

Hamid, M., Dayana, I., Satria, H., Ramdan, D., Junaidi, Siregar, M. F., Sholeha, D., Marbun, J., & Wijoyo, H. (2025). Porous hard carbon derived from coconut biomass waste as electrode material for supercapacitor. *JCIS Open*, *19*, 100147. https://doi.org/10.1016/J.JCISO.2025.100147

He, X., Ling, P., Yu, M., Wang, X., Zhang, X., & Zheng, M. (2013). Rice husk-derived porous carbons with high capacitance by ZnCl2 activation for supercapacitors. *Electrochimica Acta*, *105*, 635–641. https://doi.org/10.1016/J.ELECTACTA.201

3.05.050

Hwang, Y. J., Jeong, S. K., Shin, J. S., Nahm, K. S., & Stephan, A. M. (2008). High capacity disordered carbons obtained from coconut shells as anode materials for lithium batteries. *Journal of Alloys and Compounds*, *448*(1–2), 141–147. https://doi.org/10.1016/J.JALLCOM.2006.10.036

Jia, H. L., Chai, K. Y., Ji, P. C., & Lu, Y. J. (2025). High capacity peanut shell-based hard carbon as a negative electrode for sodium-ion batteries. *Sustainable Energy & Fuels*, *9*(7), 1822–1828. https://doi.org/10.1039/D4SE01617C

Kong, L., Li, C., Sun, R., Zhang, S., Wang, Y., Xiang, J., Hu, S., Wang, D., Leng, C., & Hu, X. (2024). Thermal pretreatment of willow branches impacts yield and pore development of activated carbon in subsequent activation with ZnCl2 via modifying cellulose structure. *Chinese Journal of Chemical Engineering*, *69*, 227–237. https://doi.org/10.1016/J.CJCHE.2024.01.014

Kongthong, T., Tuantranont, S., Primpray, V., Sriprachuabwong, C., & Poochai, C. (2023). Rechargeable lithium-ion dual carbon batteries utilising a quasi-solid-state anion co-intercalation electrolyte and palm kernel shell-derived hard carbon. *Diamond and Related Materials*, *132*, 109680. https://doi.org/10.1016/J.DIAMOND.2023.109680

Lee, K. C., Lim, M. S. W., Hong, Z. Y., Chong, S., Tiong, T. J., Pan, G. T., & Huang, C. M. (2021). Coconut Shell-Derived Activated Carbon for High-Performance Solid-State Supercapacitors. *Energies 2021, Vol. 14, Page 4546*, *14*(15), 4546. https://doi.org/10.3390/EN14154546

Lee, S., Ha, H., Dunsmore, E., & Ali, S. (2026). *Zinc Anode Modi fi cation Using Biomass-Based Materials for High-Performance Zinc-Ion Batteries*. https://doi.org/10.1155/er/9436619

Li, J., Lin, Q., Wang, Z., Du, A., Luo, H., & Liu, Y. Q. (2023). Hierarchical porous carbon with high specific surface area and superb capacitance made from palm shells for supercapacitors. *Diamond and Related Materials*, *135*, 109852. https://doi.org/10.1016/J.DIAMOND.2023.109852

Liang, C., Wang, P., Li, Y., & Yu, K. (2022). Biomass based composite used as anode materials: Porous ZnO anchored on the rice husk-derived carbon substrate for Li-ion batteries. *Materials Science and Engineering: B*, *278*, 115656. https://doi.org/10.1016/J.MSEB.2022.115656

Lin, W., Zhao, S., Lu, B., Jiang, F., Lu, Z., & Xu, Z. (2024). Structures, performances and applications of green biomass derived carbon in lithium-ion batteries. *Energy Mater 2024;4:400078.*, *4*(5), N/A-N/A. https://doi.org/10.20517/ENERGYMATER.2024.09

Liu, D., Zhang, W., Lin, H., Li, Y., Lu, H., & Wang, Y. (2015). Hierarchical porous carbon based on the self-templating structure of rice husk for high-performance supercapacitors. *RSC Advances*, *5*(25), 19294–19300. https://doi.org/10.1039/C4RA15111A

Liu, G., Qin, S., Zhang, X., You, D., Zhang, Y., Zeng, X., Zhang, Y., & Zhu, Z. (2025). *A new opportunity for biomass-derived carbon in highly stable Li- O 2 battery : A review*. *0091*, 1–19.

Liu, J., Kuli, Z., Toshtay, K., Lee, J., Askaruly, K., & Azat, S. (2026). Biomass-derived activated carbon/MXene composites as supercapacitor electrodes. *Electrochemistry Communications*, *188*, 108166. https://doi.org/10.1016/J.ELECOM.2026.108166

Luna-Lama, F., Morales, J., & Caballero, A. (2021). Biomass porous carbons derived from banana peel waste as sustainable anodes for lithium-ion batteries. *Materials*, *14*(20), 5995. https://doi.org/10.3390/MA14205995/S1

Merum, D., & Kang, M. (2025). *From biomass to energy storage : sustainable carbon materials for next - generation supercapacitors*. *7*.

Mi, J., Wang, X. R., Fan, R. J., Qu, W. H., & Li, W. C. (2012). Coconut-Shell-Based Porous Carbons with a Tunable Micro/Mesopore Ratio for High-Performance Supercapacitors. *Energy and Fuels*, *26*(8), 5321–5329. https://doi.org/10.1021/EF3009234

Misnon, I. I., Zain, N. K. M., & Jose, R. (2018). Conversion of Oil Palm Kernel Shell Biomass to Activated Carbon for Supercapacitor Electrode Application. *Waste and Biomass Valorization 2018 10:6*, *10*(6), 1731–1740. https://doi.org/10.1007/S12649-018-0196-Y

Nasreldin, M., Delattre, R., Calmes, C., Ramuz, M., Sugiawati, V. A., Maria, S., Tocnaye, J. L. de B. de la, & Djenizian, T. (2020). High performance stretchable Li-ion microbattery. *Energy Storage Materials*, *33*(August), 108–115. https://doi.org/10.1016/j.ensm.2020.07.005

Nita, C., Zhang, B., Dentzer, J., & Matei Ghimbeu, C. (2021). Hard carbon derived from coconut shells, walnut shells, and corn silk biomass waste exhibiting high capacity for Na-ion batteries. *Journal of Energy Chemistry*, *58*, 207–218. https://doi.org/10.1016/J.JECHEM.2020.08.065

Oh, Y., Seo, S. W., Yang, J., Jeong, M., & Ahn, S. (2025). *Eco-Friendly , Biomass-Derived Materials for Electrochemical Energy Storage Devices*. 1–17.

Pitchaikannu, V., Aggarwal, L. M., & Choudhary, S. (2025). Harnessing scatter radiation for sustainable energy: Coconut shell-based activated carbon electrodes for high-performance supercapacitors in radiology applications. *Radiation Physics and Chemistry*, *229*, 112470. https://doi.org/10.1016/J.RADPHYSCHEM.2024.112470

Qiu, G., Miao, Z., Guo, Y., Xu, J., Jia, W., Zhang, Y., Guo, F., & Wu, J. (2022). Bamboo-based hierarchical porous carbon for high-performance supercapacitors: the role of different components. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *650*, 129575. https://doi.org/10.1016/J.COLSURFA.2022.129575

Raza, N., Albalwai, K. M., Aziz, K., Tariq, R., Adeel, M., Kanwal, N., Salem, M. E., Asim, M., Ahmad, A., Raza, W., & Sufyan, M. (2026). Biomass derived materials for sustainable lithium batteries : A comprehensive review on recent trends , challenges and prospects. *Journal of Energy Storage*, *153*(PB), 120965. https://doi.org/10.1016/j.est.2026.120965

Reddy, Y. H., Ambika, M. R., Subramanian, K. R. V., Nagaiah, N., Srilakshmi, B. P., Kuttukaran, S. S., & Kang, D. J. (2026). Novel utilization of biomass derived carbon with activation for efficient electrode performance in supercapacitors. *Ionics 2026*, 1–36. https://doi.org/10.1007/S11581-026-07067-0

Ren, G., Qiao, Y., Jing, J., Tian, J., Wang, X., Lv, G., Wang, Y., Liu, Y., Tan, Q., & Chen, Y. (2025). Elemental regulation and ultra-micropore defects engineering for enhancing low-potential Na+ storage in biomass-derived hard carbon. *Energy Storage Materials*, *80*, 104367. https://doi.org/10.1016/J.ENSM.2025.104367

Rybarczyk, M. K., Li, Y., Qiao, M., Hu, Y. S., Titirici, M. M., & Lieder, M. (2019). Hard carbon derived from rice husk as low cost negative electrodes in Na-ion batteries. *Journal of Energy Chemistry*, *29*, 17–22. https://doi.org/10.1016/J.JECHEM.2018.01.025

Saini, P., Aggarwal, R., Joshi, A., & Bansal, S. (2026). Fabrication of activated carbon electrodes for energy storage devices using waste biomass: A review. *Journal of Power Sources*, *676*, 239868. https://doi.org/10.1016/J.JPOWSOUR.2026.239868

Saini, S., Chand, P., & Joshi, A. (2021). Biomass derived carbon for supercapacitor applications: Review. *Journal of Energy Storage*, *39*, 102646. https://doi.org/10.1016/J.EST.2021.102646

Sangprasert, T., Sattayarut, V., Rajrujithong, C., Khanchaitit, P., Khemthong, P., Chanthad, C., & Grisdanurak, N. (2022). Making use of the inherent nitrogen content of spent coffee grounds to create nanostructured activated carbon for supercapacitor and lithium-ion battery applications. *Diamond and Related Materials*, *127*, 109164. https://doi.org/10.1016/J.DIAMOND.2022.109164

Sugiawati, V. A., Vacandio, F., Yitzhack, N., Ein-Eli, Y., & Djenizian, T. (2020). Direct pre-lithiation of electropolymerized carbon

nanotubes for enhanced cycling performance of flexible li-ion micro-batteries. *Polymers*, *12*(2). https://doi.org/10.3390/polym12020406

Sun, H., Ying, Z., Chen, X., Zheng, X., Dou, B., & Cui, G. (2026). Synergistic enhancement of coconut shell biochar for energy storage via KOH activation and electrooxidation. *Renewable Energy*, *263*, 125549. https://doi.org/10.1016/J.RENENE.2026.125549

Surib, N. A., Amirul, M., Abdah, A. M., Syakirah Ismail, F., Weng Pin, W., Ezzah, F., Latif, A., Norhaffis Mustafa, M., Walvekar, R., & Khalid, M. (2026). Microwave-Pyrolysed Rice Husk-Derived Activated Carbon as a Sustainable Anode Material for Lithium-Ion Half-Cell Batteries. *Advance Sustainable Science Engineering and Technology*, *8*(2), 02602027–02602027. https://doi.org/10.26877/ASSET.V8I2.2740

Technology, E., Aurelia, K., Silvia, D., Wardhani, R., Makhmudi, H., & Adi, E. (2025). *Journal of Renewable Characteristics of Anodes for Li-ion Batteries from Coconut Shell Activated Carbon as*. *12*(2), 79–84.

Tripathy, A., Mohanty, S., Nayak, S. K., & Ramadoss, A. (2021). Renewable banana-peel-derived activated carbon as an inexpensive and efficient electrode material showing fascinating supercapacitive performance. *Journal of Environmental Chemical Engineering*, *9*(6), 106398. https://doi.org/10.1016/J.JECE.2021.106398

Vo, T. N., Le, V. T., Dang, N. K., Le, M. L. P., Nguyen, V. H., Tran, V. M., Nguyen, M. T., Tran, N. H. T., Nguyen, T. L., & Kim, I. T. (2024). ZnCl2-based activation for converting spent coffee grounds into a robust anode for Li-ion batteries. *Biomass and Bioenergy*, *181*, 107058. https://doi.org/10.1016/J.BIOMBIOE.2024.107058

Wang, J., Yang, Z., Pan, F., Zhong, X., Liu, X., Gu, L., & Yu, Y. (2015). Phosphorus-doped porous carbon derived from rice husk as anode for lithium ion batteries. *RSC Advances*, *5*(68), 55136–55142. https://doi.org/10.1039/C5RA08148C

Wang, L., Schnepp, Z., & Titirici, M. M. (2013). Rice husk-derived carbon anodes for lithium ion batteries. *Journal of Materials Chemistry A*, *1*(17), 5269–5273. https://doi.org/10.1039/C3TA10650K

Wei, G. (2024). Recent Trends in Biomass Materials. *Applied Sciences 2024, Vol. 14, Page 1766*, *14*(5), 1766. https://doi.org/10.3390/APP14051766

Xiang, J., Lv, W., Mu, C., Zhao, J., & Wang, B. (2017). Activated hard carbon from orange peel for lithium/sodium ion battery anode with long cycle life. *Journal of Alloys and Compounds*, *701*, 870–874. https://doi.org/10.1016/J.JALLCOM.2017.01.206

Yan, B., Han, C., Dai, Y., Li, M., Wu, Z., & Gao, X. (2024). Biomass derived hard carbon materials for sodium ion battery anodes: Exploring the influence of carbon source on structure and sodium storage performance. *Fuel*, *371*, 132141. https://doi.org/10.1016/J.FUEL.2024.132141

Yılmaz, M., Baykal, M., Farghaly, A. A., & Demir, M. (2023). Production of Porous Carbon by the Synergistic Chemical and Physical Activations and its Capacitive Performance. *Journal of the Institute of Science and Technology*, *13*(3), 1888–1901. https://doi.org/10.21597/JIST.1180016

Yu, W., Wang, H., Liu, S., Mao, N., Liu, X., Shi, J., Liu, W., Chen, S., & Wang, X. (2016). N, O-codoped hierarchical porous carbons derived from algae for high-capacity supercapacitors and battery anodes. *Journal of Materials Chemistry A*, *4*(16), 5973–5983. https://doi.org/10.1039/C6TA01821A

Zhao, Zhengping, Shen, S., Li, Y., Chen, Q., Zhong, M., & Chen, X. (2020). Electrochemical Performance of Carbon derived from Bamboo Shoot as Anode Materials for Lithium-ion Battery. *International Journal of Electrochemical Science*, *15*(5), 3846–3855. https://doi.org/10.20964/2020.05.52

Zhao, Zhiqiang, Su, Z., Chen, H., Yi, S., Zhang, W., Niu, B., Zhang, Y., & Long, D. (2022). Renewable biomass-derived carbon-based hosts for lithium–sulfur batteries. *Sustainable Energy & Fuels*, *6*(23), 5211–5242. https://doi.org/10.1039/D2SE01164F

Zhu, B., Liu, B., Qu, C., Zhang, H., Guo, W., Liang, Z., Chen, F., & Zou, R. (2018). Tailoring biomass-derived carbon for high-

performance supercapacitors from controllably cultivated algae microspheres. *Journal of Materials Chemistry A*, *6*(4), 1523–1530. https://doi.org/10.1039/C7TA09608A