Applications of Biomass-Derived Carbon in Supercapacitor Energy Storage: A Review

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Abstract: *Biomass-derived carbon materials have garnered significant attention as sustainable, low-cost electrode candidates for supercapacitors owing to their abundant availability and tunable properties. This review categorizes biomass sources into plant-based, animal-based, marine-based, and human waste-based, highlighting their structural diversity and electrochemical potential. Key structural factors, such as pore size distribution and surface functional groups, are discussed in relation to their impact on capacitance performance. Hierarchical porosity enhances ion transport and charge storage, whereas heteroatom doping and oxygen-containing groups contribute to pseudocapacitive behavior. By tailoring these features, biomass carbon materials can achieve a high specific capacitance, excellent rate capability, and cycling stability. Future research directions include precise structural control, exploration of novel biomass precursors, and the development of scalable green synthesis methods. This review aims to provide insights into the rational design of biomass-derived carbons for environmentally friendly and high-performance energy storage applications.*

Keywords: Biomass-derived activated carbon; Supercapacitors; Structural effect.

1. INTRODUCTION

With increasing global energy consumption and increasingly severe environmental problems, developing efficient and green energy storage technology has become a current research hotspot [1]. Supercapacitors, also known as electrochemical capacitors, are widely used in portable electronic devices, electric vehicles, and smart grids because of their high power density, long cycle life, and fast charge and discharge characteristics [2]. Supercapacitors can be divided into electric double-layer capacitors (EDLCs) and pseudocapacitors according to their energy storage mechanisms [3]. Among them, carbon-based materials are the main force of EDLC electrode materials because of their excellent conductivity, chemical stability, and adjustable structure [4-6].

The preparation of low-cost, environmentally friendly, high-performance carbon materials has become a research focus in recent years. Among the many carbon sources, biomass has gradually become an essential precursor for preparing high-performance carbon materials because of its wide range of sources, strong renewability, and diverse intrinsic structures [7]. Hydrolysis, hydrothermal carbonization, and chemical activation can convert biomass into carbon materials with rich pore structures and heteroatom doping, which exhibit excellent electrochemical properties [8].

This review aims to start from the source of biomass and sort out the research progress of carbon materials derived from different types of biomass raw materials (such as wood fiber, agricultural waste, and food waste) in the field of supercapacitors, explore the relationship between their structural characteristics and electrochemical properties, and summarize the current challenges and future development directions to provide a theoretical basis and practical reference for the development of green energy storage materials.

2. SOURCES OF BIOMASS CARBON

Biomass-derived carbon materials can be classified into four main categories based on their sources: plant-based, animal-based, marine-based, and human waste-based sources. As shown in Fig. 1, each source type has unique characteristics that influence the properties and performance of the carbon materials derived from them, ultimately determining their potential in applications such as supercapacitors and other energy storage devices. The materials from each source undergo different conversion processes, resulting in carbon materials with varying pore structures, surface chemistry, and electrochemical properties.

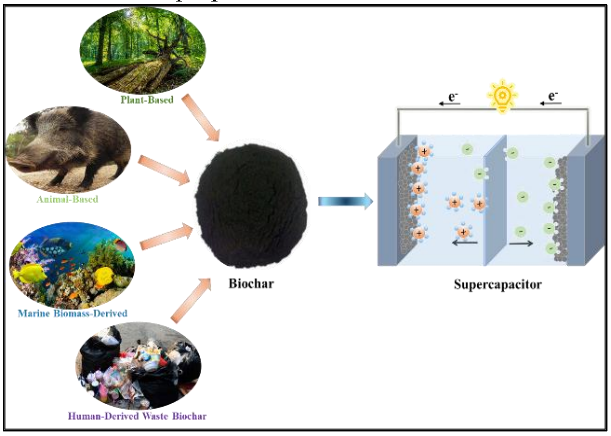

Fig. 1. Classification and sources of biomass carbon materials

2.1 Plant-Based Sources

Plant-based biomass is one of the most common and widely used carbon sources. These include wood, agricultural residues (such as rice husks, corn stalks, and sugarcane bagasse), plant leaves, stems, and other plants [9, 10]. The primary organic components in plants are cellulose, hemicellulose, and lignin, which can be converted into carbon materials with various structures and properties when subjected to pyrolysis. The preparation of porous carbon from biomass using plants has been widely studied, as shown in Fig. 2, where biomass is carbonized to obtain an intermediate biomass carbon product, which has a porous structure on the surface of the carbon material after activation by KOH and other activation.

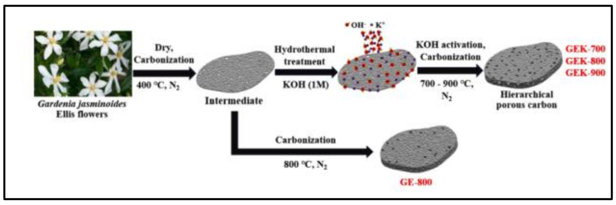

Fig. 2. Schematic of the preparation of hierarchical porous carbon using Gardenia jasminoides Ellis flowers as biomass precursors [11].

Plant-based biomass offers several advantages, including low raw material costs and widespread availability of raw materials. Agricultural and wood waste are abundant, and the technology for converting these materials into carbon materials is relatively well-established. These carbon materials generally exhibit a high surface area and well-developed porosity, making them suitable for energy storage applications, such as supercapacitors. Plant-based biomass is resource-rich and easily accessible compared to other sources, making it ideal for sustainable carbon material production.

Table 1. Specifications adopted for simulated inverter

Biomass	Specific capacitance (F/g)	Current density (A/g)	Electrolyte	Ref
Canada goldenrod	320	0.1	6 M KOH	[12]
Date leaves	107	0.5	0.1 M H_2SO_4	[13]
Paper mulberry juice	428	0.5	6 M KOH	[14]
Mangosteen husk	285	0.2	6 M KOH	[15]
Nelumbo nucifera	323.66	0.1	6 M KOH	[16]
Snake gourd pericarp	206	1	1 M H_2SO_4	[17]
Waste cornhusk	149	1	Seawater	[18]
Rotten wood	350	1	6 M KOH	[19]

2.2 Animal-Based Sources

Animal-based biomass includes bones, leather, hair, feathers, and other animal by-products. These materials are typically rich in protein, fat, and amino acids. Through pyrolysis or chemical activation, animal-derived biomass can be transformed into carbon materials with a high nitrogen content, which confers unique electrochemical properties [20].

Carbon materials from animal sources tend to have more complex chemical structures, providing electrochemical performance that is distinct from that of plant-based carbon materials [21]. Nitrogen-doped carbon materials offer enhanced conductivity and electrochemical activity, making them suitable for applications that require high charge storage and fast charge/discharge rates [22]. Although animal-based biomass is relatively scarce and more expensive than plant sources, its unique chemical composition and electrochemical performance make it advantageous for specific applications such as high-power density supercapacitors and fuel cells.

2.3 Marine-Based Sources

Marine-based biomass refers to materials obtained from marine organisms such as seaweed, algae, and fishery waste. Seaweed and algae are rich in polysaccharides, proteins, minerals, and other bioactive substances [23-25]. Marine biomass can be converted into carbon materials via pyrolysis, chemical activation, or hydrothermal carbonization. Marine organisms generally have lower densities and faster growth rates, making them a sustainable source of biomass [26].

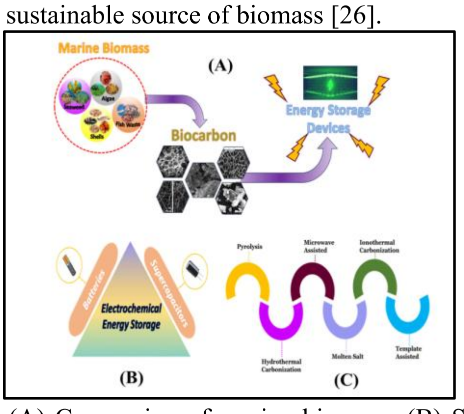

Fig. 3. (A) Conversion of marine biomass. (B) Storage options for electrical energy, and (C) strategic protocols to convert biocarbon [2].

As shown in Fig. 3, marine-derived carbon materials often contain minerals such as sulfur, phosphorus, and nitrogen, which can have catalytic effects and improve the electrochemical properties of the materials. Carbon materials from marine sources exhibit good conductivity [2], high surface area, and unique pore structures, making them promising for high-efficiency capacitors, energy storage devices, and other applications. Furthermore, marine biomass is renewable and offers an environmentally friendly option for carbon material production, which aligns with the growing emphasis on sustainable development.

2.4 Human Waste-Based Sources

Human waste-based biomass includes municipal solid waste (MSW), sewage sludge, food waste, and other urban byproducts [27]. With the increasing global population, the amount of waste generated has steadily increased, making waste recycling and resource recovery essential for environmental protection and sustainable development [28-30]. The organic components of human waste, such as carbohydrates, fats, and proteins, can be converted into carbon materials through pyrolysis or hydrothermal carbonization.

Carbon materials derived from human waste sources exhibit good electrochemical properties and offer a solution to waste disposal issues, providing significant environmental benefits to the society. These abundant and low-cost biomass sources offer a sustainable and economical alternative to the production of carbon materials [31]. Carbon materials derived from waste typically have more complex structures, which can be optimized through activation and modification processes to improve their capacitance. These materials have potential applications in energy storage, environmental remediation, and other fields, making them highly suitable for large-scale sustainable energy solutions.

3. EFFECT OF CARBON STRUCTURE ON CAPACITOR PERFORMANCE

The microstructure and surface chemistry of these materials largely determine the electrochemical performance of biomass-derived carbon materials in supercapacitors. Properly tuning the pore structure and surface functional groups of biomass carbon can enhance its specific surface area, electrical conductivity, and charge storage capabilities, leading to superior capacitive behavior. This chapter discusses two significant structural aspects that affect the capacitive performance of biomass carbon: the pore structure and surface functional groups.

3.1 Pore size distribution

The pore structure is one of the most critical factors influencing the capacitance performance of biomass carbon. The energy storage mechanisms in supercapacitors mainly rely on the interfacial interactions between the electrode surface and electrolyte, particularly through electric double-layer capacitance (EDLC) and pseudocapacitance [32, 33]. An appropriate pore size distribution not only affects ion diffusion and storage but also directly determines the specific capacitance and rate performance of the material.

Biomass-derived carbon materials often exhibit hierarchical porous structures composed of micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm). Micropores provide many sites for charge accumulation and are essential for the formation of electric double layers [34, 35]. Mesopores facilitate ion transport and improve the effective utilization of the surface area, whereas macropores support fast ion migration and efficient electrolyte infiltration, particularly at high current densities. Therefore, constructing a well-connected hierarchical pore network with an optimized proportion of pore sizes is key to achieving high-performance supercapacitor electrodes [36, 37].

The pore structure can be tuned by controlling the carbonization temperature, selecting appropriate activation agents (such as KOH or $ZnCl_2$), or employing templating strategies (e.g., SiO_2 or $CaCO_3$ templates). For instance, low-temperature pyrolysis typically favors micropore formation, whereas high-temperature activation promotes the development of meso- and macropores. Tailored pore architectures can be designed for high or high-power densities based on specific application requirements.

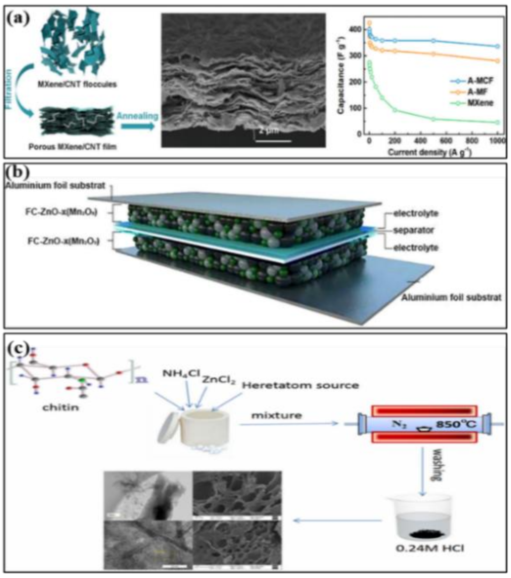

Fig. 4. (A) Schematic diagram of A-MCF preparation [38]. (B) Schematic showing the preparation process of FC-ZnO-X(Mn_2O_3) [39]. (C) Schematic showing the preparation process of N, Fe_X, S_Y-PC [40].

3.2 Surface Functional Groups

In addition to the pore structure, the surface functional groups significantly influence the electrochemical behavior of biomass carbon, particularly in enhancing the pseudocapacitive properties and electrolyte compatibility. As shown in Fig. 4, the common surface functionalities include oxygen-containing groups [41] (such as carboxyl, hydroxyl, and carbonyl groups), heteroatom dopants [42] (e.g., nitrogen, sulfur, and phosphorus), and surface-active sites [38] associated with structural defects.

3.2.1 Oxygen-containing functional groups

Oxygen-containing functional groups improve the hydrophilicity of carbon surfaces, enhancing wettability and facilitating better interactions with aqueous electrolytes. This accelerates ion transport and improves the device response rate. Moreover, some oxygen functional groups can participate in redox reactions, contributing to pseudocapacitance and increasing the specific capacitance [39, 43]. However, excessive oxygen groups may lead to undesirable side reactions and reduced stability, highlighting the importance of controlled oxidation of the surface.

3.2.2 Heteroatom doping

Heteroatom doping is another effective strategy for enhancing the performance of carbon materials. Nitrogen doping introduces functionalities such as pyrrolic N, graphitic N, and amino groups, which increase the electron density and promote charge transfer [44, 45]. Sulfur and phosphorus [40, 46, 47] doping can introduce additional electrochemically active sites and improve the pseudocapacitive contribution [48, 49]. These dopants also influence the electrical conductivity and defect density, enhancing the electrochemical kinetics.

As shown in Table.2, compared with single or co-doped heteroatoms, multi-heteroatom doping introduces a larger asymmetric spin and charge density on carbon atoms. N, S, and P doping can enhance the pseudocapacitance and electronic conductivity, introduce n-type dopants with polarized surfaces as pseudo sites, and stabilize oxygen functional groups by improving the reaction stability.

3.2.3 Surface-active

Surface-active sites, such as edges of graphitic domains and structural defects, also play a vital role in the charge storage process. These defects enhance electron transport within the carbon matrix and serve as active centers for redox reactions, imparting a pseudocapacitive behavior to the material [50].

In summary, the pore structure and surface functionalities of biomass carbon work synergistically to determine its capacitive performance. By carefully tailoring these structural and chemical features, biomass-derived carbon materials can be optimized to exhibit a high specific capacitance, excellent rate capability, and long-term cycling stability in supercapacitor applications.

Table 2. Supercapacitor performance of heteroatom doped biomass carbon electrodes

Biomass	Heteroatoms (at%)	Specific capacitance (F/g)	Current density (A/g)	Electrolyte	Ref
Gelatin	N (0.88)	385	0.05	6 M KOH	[51]
Cashmere	N (4)	460	0.5	1 M H_2SO_4	[52]
Fish gill	N (0.72)	334	2	6 M KOH	[53]
Elm flower	N, S (2.21, 6.06)	275	1	6 M KOH	[54]
Rape pollen	N, S (4.05, 0.27)	361.1	1	6 M KOH	[55]
Rice wine lees	N, S (0.59, 0.37)	433.5	1	6 M KOH	[56]
Peanut meal	N, S, P (11.2, 0.64, 0.82)	525	1	1 M H_2SO_4	[57]
Laver	S, P, K ,Mg, Ca	119.8	1	6 M KOH	[58]

4. CONCLUSION AND OUTLOOK

Biomass-derived carbon materials have emerged as a promising class of sustainable and cost-effective electrode materials for supercapacitor applications. Their diverse sources, abundant availability, and tunable structures render them ideal candidates for next-generation energy storage devices. This review outlines the classification of biomass sources, discusses the effects of pore structure and surface functional groups on electrochemical performance, and emphasizes the importance of structure-property relationships in optimizing capacitance behavior.

Specifically, hierarchical porous structures provide efficient ion transport pathways and large surface areas for charge storage, while surface functional groups, particularly heteroatom dopants, significantly enhance conductivity and contribute additional pseudocapacitance through faradaic reactions. Thus, the synergistic regulation of the physical architecture and chemical composition is essential for improving the specific capacitance, rate capability, and long-term stability of biomass carbon electrodes.

Several key challenges and opportunities remain in this field. First, achieving precise control over the pore structure and surface chemistry during synthesis is critical for the rational design of high-performance materials. The development of scalable, green, and low-energy production methods is necessary to translate laboratory research into industrial applications. Second, further exploration of novel biomass sources, especially those with intrinsic functional elements, can broaden the design space and improve material performance. Combining biomass carbon with other functional materials, such as metal oxides, conducting polymers, or MXenes, may enable hybrid systems with enhanced electrochemical properties.

Moreover, future research should emphasize understanding the underlying mechanisms of charge storage using advanced characterization techniques and theoretical modeling. The integration of machine learning and data-driven design approaches may accelerate the discovery of optimized biomass carbon materials.

In conclusion, with continued innovation in material design, processing techniques, and performance evaluation, biomass-derived carbon materials hold great potential for developing environmentally friendly, high-performance, and economically viable energy storage systems.

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