



# Enhancing Supercapacitor Performance with Biomass-Derived Carbon Materials: A Review of Dimensional Innovations

M. Gowtham <sup>a</sup>, N. Senthil Kumar <sup>a,\*</sup>, Murugan Balaji <sup>b</sup>, Chandrasekar Sivakumar <sup>c</sup>

<sup>a</sup> Department of Physics, Kongunadu Arts and Science College, Coimbatore-641 029, Tamil Nadu, India.

<sup>b</sup> Department of Electrical & Computer Engineering, National University of Singapore, Singapore.

<sup>c</sup> Department of Physics, National Chung Hsing University, Taichung City 40227, Taiwan.

\* Corresponding author Email: [senthilkumar\\_physics@kongunaducollege.ac.in](mailto:senthilkumar_physics@kongunaducollege.ac.in)

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**Abstract:** Supercapacitor high-power density, rapid charge/discharge rates, long lifespan, and environmental friendliness have positioned them as extremely promising energy storage options. This study examines the physical and chemical characteristics of several biomass materials and their impact on supercapacitor performance. Additionally, we delve into the classification and fundamental concepts of supercapacitors. Biomass-derived carbon compounds exhibit abundant surface features and naturally occurring hierarchical structures that enhance electrochemical reactions, including diffusion and ion transfer. Historically, biomass has been the primary raw material for synthesizing innovative porous carbon compounds, representing a significant advancement in electrode materials for supercapacitors. Our study emphasizes the potential applications of one-, two-, and three-dimensional carbon compounds derived from biomass as electrode materials for supercapacitors by reviewing the latest research in this field. Additionally, we discuss the challenges faced today and the opportunities for enhancing the efficiency of carbon-based supercapacitor electrodes in the future.

**Keywords:** Biomass, Supercapacitor, Nanoparticles, Biodegradable Materials

## 1. Introduction

The global energy crisis, exacerbated by climate change and environmental pollution largely stemming from fossil fuel consumption, calls for innovative energy solutions. Electrochemical supercapacitors (ESCs) have emerged as promising energy storage solutions. They are categorized into two types based on their energy storage mechanisms: electrostatic double-layer capacitors (EDLCs) and faradaic pseudocapacitors. EDLCs generate an electrical double-layer (EDL) at the electrode-electrolyte interface through reversible ion adsorption and desorption. The surface area of the electrode available for ion electroadsorption determines the capacitance of an EDLC [1-5].

There are numerous scientific and practical advantages in creating high-value carbon electrode materials from biomass for a sustainable future. The quest for affordable, eco-friendly, and scalable energy solutions has driven the development of porous carbon derived from biomass. This material possesses a highly active surface crucial for achieving high specific capacity, along with a well-defined porous structure

essential for power applications. Biomass, including plant and animal-based materials from natural sources, provides a renewable and abundant resource for creating these advanced carbon materials [6].

The abundance of biomass resources, including energy crops, agricultural waste, wood residues, urban household waste, aquatic plants, and algae, offers a potential alternative to petroleum-based products. These resources are biodegradable, renewable, environmentally friendly, and non-toxic, making them attractive options for various industries. Biomass is integral to various industries, including food, biology and medicine, agriculture, and energy storage. The intricate morphologies and nanostructures of natural biopolymers like starch, chitosan, chitin, and cellulose make them ideal for use in supercapacitors. Biomass-derived materials are ideal for carbon electrode applications as they develop unique porous architectures and enhanced electrical conductivity through high-temperature thermochemical processes. Moreover, composites that maximize the physical and chemical characteristics of each component are produced when biomass materials are mixed with

conductive elements such as conductive polymers, carbon materials, 2D materials, metal nanoparticles, and transition metal oxides. Additionally, the utilization of biopolymers has been explored in research on functional supercapacitor electrolytes. The hydrophilic groups in biopolymers enhance the solubility of salts and the transport capabilities of cations, thereby improving the wetting properties of polar liquids [7-14].

Three types of supercapacitors can be notable by their charge storage mechanisms: 1) Pseudocapacitors, which store energy through rapid surface-controlled redox reactions; 2) Electric double-layer capacitors (EDLCs) store charge by adsorbing ions on the surface of the electrodes; and 3) Hybrid supercapacitors, which combine the characteristics of both EDLCs and pseudocapacitors to attain higher energy and power densities [15-21].

Several studies have shown that biomass can be efficiently converted using a variety of techniques into carbon-based functional materials with customized micro- and nanostructures and modifiable surface chemistries. By employing various bio-template designs, carbon materials with one, two, and three-dimensional architectures can be produced, utilizing the diverse microstructures found in natural biomass. This review aims to categorize the latest advancements in synthetic approaches and address the emerging challenges associated with biomass-derived carbon materials of varying dimensions for supercapacitor applications. The advantages of these materials' unique properties for enhancing supercapacitor performance are highlighted, with a focus on the distinctive qualities associated with each dimensional structure. Finally, a brief discussion is provided on the primary emerging trends and current challenges in this field.

## 2. Properties of Biomass-Based Materials

Based on their origin and chemical makeup, biopolymers are divided into three groups: proteins (such as collagen and gelatin), polysaccharides (such as cellulose, chitosan/chitin, alginate, and starch), and microbial polymers (such as bacterial cellulose and polyhydroxyalkanoates) [22]. Among these, biopolymers found in cellulose, starch, alginate, chitosan, and chitin are commonly employed in supercapacitors.

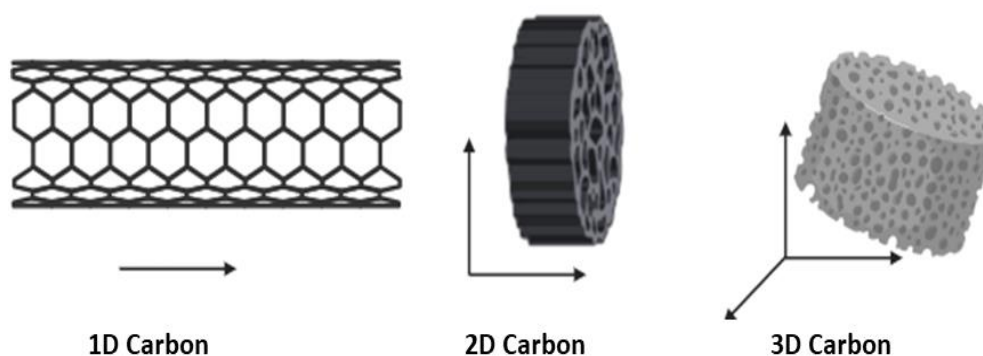
Chitin, a common biopolymer, is abundant in the cell walls of fungi, insects, and the shells of crustaceans such as shrimp and crabs [23]. The fundamental building block of this compound is the monomer of 2-acetamido-2-deoxy- $\beta$ -D-glucose, linked by  $\beta$ -1, 4-glycosidic bonds. Chitin undergoes enzymatic or chemical deacetylation to produce chitosan, a copolymer with a degree of N-deacetylation (DD) exceeding 50%. Chitosan consists of N-acetylglucosamine and D-glucosamine units joined by  $\beta$ -1, 4-glycosidic linkages, and its amino groups can be protonated at pH 6.5, making it highly soluble in various acids, including formic, hydrochloric, and acetic acids.

Cellulose, an essential part of plant cell walls, is one of the most abundant biopolymers in nature. It consists of linear chains of glucose units connected by  $\alpha$ -(1-4)-glycosidic linkages [26, 27]. With three alcohol hydroxyl groups at positions C2, C3, and C6 on each glucose unit, cellulose promotes hydrogen bonding between and within molecules. These linkages result in the formation of primary cellulose (elementary fibrils), which then aggregate to form larger microfibrils and macrofibrils. The composition of the cell wall is also influenced by lignin and hemicellulose [28].

Cellulose is insoluble in water at ambient temperature and in diluted alkali solutions, as well as in common organic solvents such as ether, acetone, and alcohol. Its exceptional stability and structural integrity make cellulose suitable for supercapacitor applications due to its porosity, flexibility, and ability to bond with conductive materials.

Alginate, another important biopolymer, consists of alternating mannuronic and guluronic acid residues. There are over 200 different varieties of alginates, varying in block lengths and concentrations of M and G residues. The M-blocks from the polymer chain, while the G-blocks interact with divalent cations to create intermolecular crosslinks.

Alginate, due to its higher viscosity at low pH, can encapsulate other substances and induce significant gel formation. Calcium alginate gel forms when alginate replaces specific H<sup>+</sup> and Na<sup>+</sup> ions in the presence of Ca<sup>2+</sup>. Modifying the molecule's reactive carboxylic acid groups allows for the production of functional materials for various applications [29-30]. Figure 1 shows 1D, 2D, and 3D carbon nanostructures.



**Figure 1.** 1D, 2D, and 3D carbon nanostructures

### 3. 1-D Biomass Carbon Materials for Supercapacitors

Research has shown the excellent suitability of one-dimensional (1D) biomass nanostructures, typically exhibiting fibrous and tubular shapes, for high-performance supercapacitors and other applications. These structures offer several advantages:

**Mechanical Properties:** Fibrous structures offer high-strength, self-supporting materials ideal for separators or electrodes, thanks to their high Young's modulus of 138 GPa and strength of around 2-3 GPa [31-33].

**Chemical Modification:** The reactive hydroxyl groups on the fiber surface facilitate straightforward chemical modification with highly active compounds. This allows for the creation of fiber-based composite electrodes, enabling adjustments to the ratio of active materials to enhance electrochemical performance [33-35].

**Network Formation:** Fibrous geometries with high aspect ratios, such as those found in bacterial secretions or higher plant tissues, can be assembled to create interconnected, binder-free networks. These networks form robust substrates or films ideal for flexible energy storage systems [36-38].

**Processing and Stability:** Nanofibers are easy to process, have large specific surface areas, good flexibility, and are thermally stable. These characteristics make it possible to create thermally stable, pore-structure-controlled non-porous membranes that promote ion and electron transport. [39-40].

**Electron Conduction:** The direct current path provided by one-dimensional linear channels enhances electron transmission compared to particle electrodes [41-42].

Moreover, certain biomass materials feature hollow tubular structures that serve as reservoirs for the electrolyte. Moreover, these structures have a larger specific surface area compared to nanofibers, leading to more active contact sites [43].

Besides possessing diverse structural and surface chemical properties, biomass-based carbon materials, with their typical one-dimensional morphology, can be utilized in various materials or devices through different preparation methods. Examples of fibrous biomass include flax, ramie, and bacterial cellulose, while tubular structures are found in cotton, kapok, and willow catkins [44-46].

Furthermore, these structures offer a larger specific surface area compared to nanofibers, resulting in more active contact sites. Various techniques have been employed to produce different one-dimensional carbon compounds from biomass, showcasing exceptional electrochemical capabilities. Cellulose, the most abundant renewable biomass fiber on Earth, exhibits significant potential due to its high carbon content, abundant surface chemical characteristics, excellent mechanical strength, large specific surface area, thermal stability, and ease of processing. These attributes make cellulose an excellent candidate for advanced energy storage devices. [47-50].

### 4. 2-D biomass carbon materials for supercapacitors

Below are several advantages of employing two-dimensional 2D carbonaceous materials with abundant sp<sup>2</sup> hybridizations for energy conversion and storage:

**Enhanced In-plane Conductivity:** The strong covalent bonds within the unique 2D structure provide high in-plane conductivity, facilitating rapid electron transport within the plane [51-53].

**Layered Porous Structure:** The large lateral size and ultra-thin atomic thickness of the two-dimensional layered porous structure decrease the distance ions need to travel, thereby enhancing ion transport efficiency [54-57].

**Large Surface Area and Active Sites:** The broad, open flat surface of 2D carbonaceous materials exposes surface atoms on all sides, providing numerous electrochemically active sites and a large specific surface area. This enhances electrode-electrolyte interactions and reduces ionic resistance. [58].

**Rich Active Surface Edge and Defect Sites:** Two-dimensional materials offer abundant active surface edges and in-plane defect sites that boost specific capacitance and promote efficient charge storage [59].

**Long Cycle Stability:** Long-term cycle stability can be achieved by employing two-dimensional porous carbon nanosheets with hierarchical pore architectures, which effectively buffer volume fluctuations during charge/discharge cycles [59].

Although graphene-based materials exhibit excellent capacitive performance, their manufacturing processes are often complex and costly. Recently, efficient techniques have been developed to produce 2D graphene-like carbon nanosheets from renewable biomass sources. These materials offer a promising and sustainable approach for fabricating carbon-based electrodes in supercapacitors [60].

For instance, Taniya Purkait *et al.* utilized KOH activation on peanut shells followed by manual exfoliation to produce nanosheets resembling few-layered graphene. The resulting carbonaceous material exhibited a high specific surface area and pore volume, thanks to numerous micropores and mesopores. The supercapacitor constructed using this material in a sulfuric acid electrolyte, without a binder, demonstrated good energy density and power density [60].

Moreover, due to their atomic-scale thickness, the flexibility of 2D materials is crucial for wearable energy devices. Xiuxiu Yu *et al.* created a freestanding activated wrinkled carbon membrane using flower petals, showing exceptional bending stability and a high specific capacitance in an all-solid, flexible supercapacitor [61]. Carbon nanosheets co-doped with nitrogen and boric acid were synthesized by Zheng Ling *et al.*, exhibiting enhanced cycle life and improved

high-rate capabilities in compressible energy storage devices [62].

## 5. 3-D Biomass Carbon Materials For Supercapacitors

The microstructures of electrode materials are crucial for their performance in energy storage devices. Increasing dimensionality effectively boosts the active surface area, enhancing capacitive performance by exposing more specific electrolyte facets [63, 64]. Furthermore, a 3D microstructure with interconnected small and large pores is essential for creating high-performance electrode materials because it shortens diffusion pathways and ensures continuous electron pathways for optimal electrical contact. [65, 66]. Efforts have been made to replicate the intricate three-dimensional structures found in natural species while reducing costs through the development of biomass-based carbon materials with 3D microstructures. Various 3D carbon architectures, including carbon aerogels, flexible carbon films, and hierarchical porous carbons, have been extensively studied and demonstrated excellent performance in supercapacitor applications.

For example, MnO<sub>2</sub> nanosheets were uniformly deposited on and inside wood carbon channels using electrodeposition [67]. The multi-channel structure allowed for effective ion penetration, leading to high mass loading, conductivity, and hierarchical pore structures. This resulted in ultra-high areal capacitances and improved rate capabilities. Moreover, combining biomass-derived porous carbon (BPC) with nanostructured  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> significantly enhanced the electrochemical performance. This combination enhanced charge transfer, redox activity, and pseudocapacitive kinetics [68].

While the continuous carbon structure promotes rapid electron transport, the continuous pore channels in the 3D network topology enable efficient ionic diffusion [69]. Using watermelon as the carbonaceous precursor, sponge-like carbon hydrogels and aerogels were developed, exhibiting excellent electrochemical performance and stability even under rigorous bending tests. Furthermore, Co<sub>3</sub>O<sub>4</sub> nanowire-loaded hierarchical porous carbonaceous aerogels showed enhanced pseudocapacitive performance [70].

In summary, carbon aerogels derived from biomass possess intriguing properties and a porous structure, making them an excellent choice for high-performance supercapacitor electrode materials.

**Table 1.** Supercapacitor Performance of Plant-Based Heteroatom-Doped Biomass Carbon Electrodes

Biomass	Electrolyte	Specific capacitance (F g <sup>-1</sup> )	Stability (%)	No. of cycles	Reference
Soybean residue	1 M H <sub>2</sub> SO <sub>4</sub>	250–260	90-95	10000	71
Clover stems	1 M H <sub>2</sub> SO <sub>4</sub>	436	99.4	30,000	72
Celery	6 M KOH	245	-	5000	73
Tobacco rods	6 M KOH	286.6	96	10,000	74
Wheat gluten	6 M KOH	350	99	10,000	75
Walnut shell	6 M KOH	462	-	5000	76
Lotus stem	6 M KOH	360.5	96	5000	77
Peach gum	6 M KOH	406	88	6000	78
Soya	1 M H <sub>2</sub> SO <sub>4</sub>	193	93	10,000	79
Perilla frutescens	6 M KOH	270	96.1	10,000	80

These materials offer efficient ion diffusion, rapid electron transport, and excellent electrochemical performance, making them attractive for energy storage applications.

The table -1 presents the specific capacitance, stability, and number of cycles for various biomass-derived carbon electrodes tested with different electrolytes. Soybean residue showed a specific capacitance ranging between 250 to 260 F g<sup>-1</sup> in 1 M H<sub>2</sub>SO<sub>4</sub> electrolyte with a stability of 90-95% over 10,000 cycles [71]. Clover stems exhibited a high specific capacitance of 436 F g<sup>-1</sup> in 1 M H<sub>2</sub>SO<sub>4</sub> with an impressive stability of 99.4% over 30,000 cycles [72]. Celery-derived carbon electrodes, tested in 6 M KOH electrolyte, achieved a specific capacitance of 245 F g<sup>-1</sup> with stability data not available and cycled up to 5,000 times [73]. Tobacco rods and Wheat gluten electrodes, also in 6 M KOH, demonstrated specific capacitance values of 286.6 and 350 F g<sup>-1</sup>, respectively, with excellent stabilities of 96% and 99% over 10,000 cycles [74, 75]. Walnut shell-derived electrodes exhibited a high specific capacitance of 462 F g<sup>-1</sup> but with stability data not available, cycled up to 5,000 times [76]. Lotus stem and Peach gum electrodes, in 6 M KOH, showed specific capacitances of 360.5 and 406 F g<sup>-1</sup>, respectively, with stabilities of 96% and 88% over 5,000 and 6,000 cycles, respectively [77, 78]. Finally, Soya-derived electrodes displayed a specific capacitance of 193 F g<sup>-1</sup> with 93% stability over 10,000 cycles in 1 M H<sub>2</sub>SO<sub>4</sub> electrolyte [79]. Perilla frutescens electrodes, tested in 6 M KOH, achieved a specific capacitance of 270 F g<sup>-1</sup> with 96.1% stability over 10,000 cycles [80].

## 6. Conclusion

Due to their abundance, adaptability, and environmental friendliness, carbon compounds derived from biomass have made significant advances in electrochemical energy storage applications in recent years. Over millions of years, natural biomass has evolved and developed a variety of intricate morphologies, including three-dimensional structures, two-dimensional nanosheets, and one-dimensional fibers. These shapes serve as templates to enhance electrochemical properties and as building blocks for flexible electrodes. The latest advancements in utilizing carbon materials sourced from biomass with different dimensions for supercapacitors are the main focus of this review. Each dimensional category offers promising electrode materials with distinct advantages. For instance, one-dimensional carbon structures are ideal for high-rate capability supercapacitors due to their shorter ion and electron transport paths, which significantly influence charge storage device capacitance, emphasizing the importance of ion diffusion and surface accessibility. Two-dimensional carbon materials excel in these aspects due to their extensive surface area exposure in the electrolyte, enhancing electrochemical performance. Three-dimensional carbon materials, with their large active surface areas, are particularly prospective candidates for high-performance supercapacitors. Despite these advancements, there are ongoing challenges and opportunities for further enhancing the performance and scalability of biomass-derived carbon materials. Future research should continue to explore the



optimization of these materials to fully harness their potential in sustainable energy storage solutions.

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#### Does this article screened for similarity?

Yes

#### Conflict of interest

The Authors declares that there is no conflict of interest anywhere.

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