MOEM

Modern Electronic Materials 2025; 11(2): 65–80
DOI 10.3897/j.moem.11.2.143665

Review Article

Recent progress in sustainable energy storage using activated carbon from biowaste for high-performance supercapacitors: a review

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Received 5 December 2024 ♦ **Accepted** 23 January 2025 ♦ **Published** 30 June 2025

Citation: Jeielayaganga VT, Keerthiga R, Venkatesh M (2025) Recent progress in sustainable energy storage using activated carbon from biowaste for high-performance supercapacitors: a review. *Modern Electronic Materials* 11(2): 65–80. https://doi.org/10.3897/j.moem.11.2.143665

Abstract

Carbon-based materials have emerged as attractive possibilities for supercapacitor applications due to their high electrical conductivity, huge surface area, and excellent stability. The potential of carbon materials, like carbon allotropes and activated carbon derived from biowaste, to enhance supercapacitor performance is examined in this paper. Activated carbon remains popular due to its high surface area and low cost, but improvements in CNTs and graphene provide enhanced conductivity and structural adaptability, increasing energy and power density. It also examines the creation of carbon composites, which combine the benefits of carbon and other materials to improve supercapacitor qualities. The main factors influencing supercapacitor performance are discussed, focusing on surface modification and nanotechnology, including electrode design, pore structure, and electrolyte compatibility. Recent study findings emphasize the relevance of sustainable synthesis processes and the materials' scalability for commercial applications. The analysis continues by identifying potential prospects in carbon-based supercapacitor research, including the incorporation of environmentally friendly material production methods and the improvement of cyclic stability for long-term use in energy storage devices. This analysis provides a solid foundation for future advancements in high-performance supercapacitor technology.

Keywords

activated carbon, biowaste, carbon activation, supercapacitor

1. Introduction

The development of novel portable devices and hybrid cars for energy conversion and storage has resulted in an increased energy demand. Many users are looking for battery, fuel cell, and electrochemical capacitor alternatives [1]. Because of scientific breakthroughs and economic expansion, the world's energy needs are continuously increasing. But fossil fuel supplies on Earth are running low. Furthermore, the usage of fossil fuels harms the ecosystem, resulting in pollution and the greenhouse effect. Consequently, nations all over the world are making significant investments in renewable and sustainable energy sources, such as wind and solar energy. To efficiently capture and use the unpredictable energy generated by these new energy sources, energy storage devices are required. Supercapacitors have a long history going

back to H.I. Becker's 1957 invention for General Electric Company, and they are widely used energy storage devices [2]. The ability of porous carbon to accumulate charge in an aqueous electrolyte was the subject of a significant investigation described in the patent. The Standard Oil Company of Ohio (SOHIO) made a significant discovery on the energy storage potential of porous carbon supercapacitors in the 1960s. They discovered that the interface between the electrolyte and the electrode is where this storage process takes place. Using porous carbon as the electrode material, the first commercial supercapacitor was created in 1970. Nippon Electric Company (NEC) acquired the capacitor license from SOHIO in 1971. NEC was then able to develop and effectively launch supercapacitors onto the market [2]. Supercapacitors, also known as electrochemical capacitors, are a novel form of energy storage device. They are not the same as conventional capacitors. It can transmit high power and store high energy in a short amount of time, combining the benefits of both conventional rechargeable batteries and dielectric capacitors [3]. Supercapacitors are categorized such as Electric double-layer capacitors (EDLCs), Pseudocapacitors (PCs) and the Hybrid capacitors (HCs) [4] as shown in Fig. 1. The electric double-layer capacitor (EDLC), a commonly used electrochemical capacitor, has a high-power density, a long life cycle (>100,000 cycles), and a short charge/discharge time, making it a better energy storage option than batteries [5]. Because of its quick and reversible charge/discharge behavior, which produces higher energy densities than EDLC, pseudocapacitors are attracting a lot of research [6]. Due to their distinct features, hybrid supercapacitors have sparked interest in the energy storage area. It is a good option for energy storage because it achieves the energy density characteristic of faradaic battery-type electrodes while delivering a high-power density and long lifespan equivalent to non-faradaic electrodes [7].

Carbon materials are commonly utilized in supercapacitors because they are inexpensive and come in a variety of forms, including powders, fibers, felts, composites, mats, monoliths, and foils [8]. Carbon-based materials are employed in a wide range of scientific and industrial applications. Carbon can exist in three different hybridization forms like *sp*, sp^2, and sp^3, which allows the development of many different amorphous and crystalline structures [9]. Because of the high Debye frequency, high-temperature superconductivity (HTS) is theoretically conceivable in systems with closely bound C atoms. Higher superconducting transition temperatures (T_C) are limited in pure C structures due to the lack of considerable electron-phonon interaction and electronic state density at the Fermi stage [10]. Not unexpectedly, carbon is sensitive to techniques that increase its superconducting, which is often weak if not insufficient [11]. Traditional carbonaceous materials, besides their high-power density and cycling stability up to 15,000 cycles, have a higher density of energy compared to rechargeable batteries like lithium-ion, which have energy densities exceeding 180 Wh/kg [12]. The use of carbon compounds with a significant degree of specific surface area as a conductive component in carbon-based nanocomposites may boost the performance of other materials such as metal oxides, MOFs, metal sulfides, and conductive polymers [13]. Carbon is now the most often used electrode material owing to its huge range of sources, Strong conduction of electricity, and sustainable and non-polluting properties. Biomass is an excellent source of carbon Material for electrodes due to its enormous specific surface area, less expensive and widespread availability. Therefore, the production of carbon materials using biomass is critical for supercapacitor development and renewable energy consumption [14]. Specifically, activated carbon is the major stream. Low-grade coal, industrial and agricultural biomass, and other

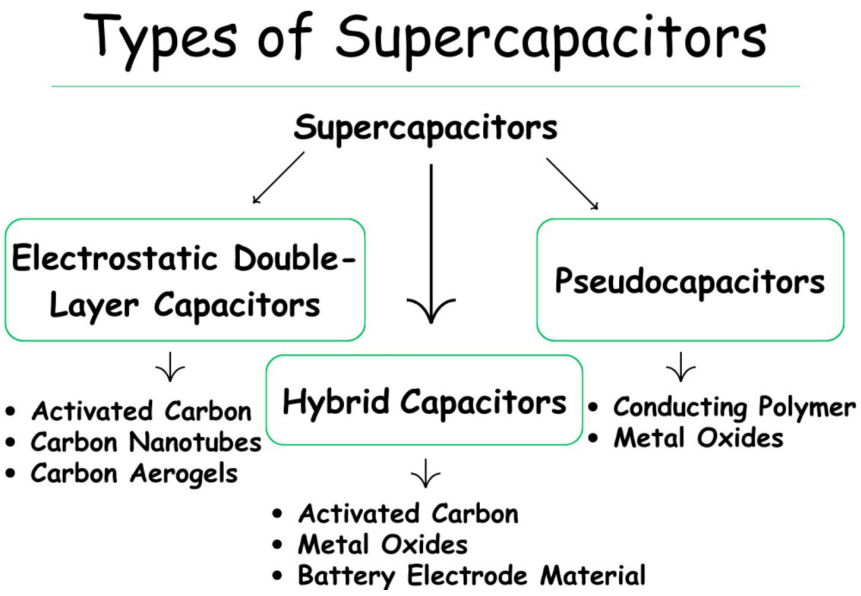

Figure 1. Types of supercapacitors

biodegradable materials are the main sources of this carbon element. The carbon can be made to have a structure that is both chemically and physically stable, including functional groups, by altering the initial preparation conditions. The different surface areas of its pores are helpful in real-world applications, and the structure of biomass carbon material offers numerous benefits [15]. The essential to the performance of the supercapacitor are charge of the electrical double layer efficiently with a large surface area and holes that are an ideal size for ions [8]. The transition metal oxides have been extensively researched as potential electrochemical materials for supercapacitors because of their environmentally friendly features, capacity to undergo various oxidation states, and high theoretical specific capacitance [16].

2. Carbon

Carbon-based materials have attracted significant interest in numerous energy-related applications because of their abundance, chemical in nature, processability, thermal stability, and the ability to customize their texture and structural properties to meet the specific needs of specific applications [17]. A wide range of new carbon materials with precisely engineered nanostructures and functionalization patterns, such as carbon nanotubes (CNTs), fullerenes, and graphene, have been developed using various physical and chemical techniques to meet the growing demand for advanced, high-performance materials in modern technology [18]. Carbon-based materials such as carbon nanotubes (CNTs) and activated carbons (ACs) are commonly used as electrodes due to their remarkable physical and molecular characteristics. These materials are versatile, come in a variety of forms (including powders, fibers, composites, aerogels, sheets, monoliths, and tubes), are simple to process, exhibit relatively inert electrochemical behavior, and have tunable porosity and electrocatalytic active sites that allow for a variability of redox reactions [19]. Numerous commercial carbon materials have elongated, narrow pores, which function as a limiting factor, especially at high current densities and rapid charge and discharge rates. This contributes to ongoing attempts to modify the pore size of carbon materials at the micropore scale ($d_{pore} < 2$ nm) and mesopore scale (2 nm < d_{pore} < 50 nm) [20].

Carbon electrodes can be constructed in elaborate configurations to increase the energy density of supercapacitors, with the goal of rivaling batteries. This improvement in energy density is often attributable to the increased capacitance of both positive and negative electrodes [21]. Finding a suitable electrode material with high energy density remains an essential challenge in energy storage devices. The ideal material should have a well-connected network for electrolytes, excellent electrical conductivity, and strong mechanical and chemical durability. As a result, carbon nanostructured materials, transition metal oxides, and conducting polymers have been widely used as active materials for charge storage. Carbon nanostructures' high surface area provides remarkable mechanical strength, chemical resilience, and electrical conductivity [22]. Porous materials with large surface areas and adjustable electrical conductivity are especially well-suited for supercapacitor electrodes [23].

3. Allotropes of carbon

Carbon and its allotropes have attracted substantial interest over the last two decades due to its potential usage in nanoelectronics, nanophotonics, sensors, bio-imaging, supercapacitors, and fuel cells [24]. Carbon allotropes such as graphene, carbon nanotubes, graphitic carbon, carbon nanofibers, templated carbons, carbide-derived carbons, carbon nano leaves, nitrogen-doped porous carbon, carbon onions, and porous carbon have been studied for their potential applications in SC electrodes, sensing, CO_2 adsorption, electrocatalysts, oxygen reduction, and other fields [25]. Carbon-based nanomaterials' have flexible and diverse bonding (sp, sp^2, and sp^3) permits them to exhibit a wide range of chemical and physical properties in multiple allotropes, which has sparked great interest in several domains of technology and science [26]. The carbon allotropes have found extensive application in a variety of sectors and are expected to remain this way in the future, particularly for applications requiring radiation [27].

3.1. Diamond

With its face-centered cubic crystal structure and exceptional physical, chemical, and electrical properties, diamond is a metastable allotrope of carbon that is highly sought-after for a range of uses [28, 29]. Conductive diamond, in particular, has emerged as an ideal electrode material for supercapacitors, fulfilling all requirements [30]. Researchers have successfully produced a conductive diamond by chemical vapor deposition (CVD) by doping it with heteroatoms like boron, nitrogen, phosphorus, and sulfur [31]. Doped diamond films including shallow acceptor and donor dopants show great promise for semiconductor device applications. The extraordinary qualities and possibilities of diamonds have generated a lot of interest, even though their high cost and processing difficulties continue to be limitations [32, 33]. Boron-doped diamond (BDD) is currently being researched as an electrode material because of its unique features when compared to normal metallic and sp^2-bonded carbon materials [34]. Particularly, BDD-based aqueous electric double-layer capacitors (EDLCs) can provide high-speed charging/discharging capabilities in small electric energy storage devices due to the BDD layer's higher bulk density compared to activated carbon [35]. When boron is added to a diamond's crystal structure, hole carriers are created, which results in p-type conductivity with an activation energy of 0.36 eV [36].

3.2. Graphene

Graphene's lightweight nature, arising from its single-layer structure, makes it an excellent candidate for applications where weight is an important consideration. The eco-friendliness of graphene, which stems from its graphite composition, raises its environmental profile for energy storage applications [37]. The name "graphene" was coined in 1986 to characterize an exclusive two-dimensional layer of carbon atoms observed in graphite intercalation compounds [38]. The graphene honeycomb network is the essential building block of various important carbon allotropes with varied dimensions [39]. It is a two-dimensional *sp*-bonded carbon atom that has sparked interest due to its features, which include high mechanical strength, a specific area of surface, thermal conductivity, conductivity, and possibly low manufacturing costs [40]. Increased surface area at the interface between an electrode and an electrolyte may help in the storage of more charges [41]. Because of its excellent properties, graphene and graphene-based materials have found usage in electronics, environmental protection, and outstanding performance. structural nanocomposites, and energy devices that incorporate both energy generation and storage [42]. Graphene has a potential surface area of up to 2630 m^2/g, which is twice the size of single-walled carbon nanotubes and substantially larger than most carbon black and activated carbons combined [43]. Metal oxide nanoparticles can bind to or embed in graphene sheets, increasing the conductivity and surface area of electrode materials while preventing particle aggregates. Furthermore, binary metal oxides perform better than single metal oxides due to the presence of mixed-valence cations in their structure. These binary oxides, with several oxidation states, can achieve longer discharge periods and larger energy densities while maintaining power density [44]. S.I. Wong et al. revealed that graphene can attain an EDL capacitance of up to 550 F/g when its complete broad surface is used [45].

3.3. Carbon aerogel

Carbon aerogels, developed in 1992, are a form of porous carbon material with outstanding electrical conductivity, large pore structure, and high particular area of surface [46]. Furthermore, carbon aerogels' porous structure with three-dimensional (3D) circular network allows for simple access to continuous ion/molecule movement and quick electron transport, making them suitable electrode materials for SCs [47]. Carbon aerogel can be created using sol-gel polycondensation of organic monomers such as resorcinol and formaldehyde, followed by polymerization [48]. According to E. Lei et al., the N-doped carbon aerogel exhibits exceptional electrochemical properties in an ionic liquid electrolyte, including high unique capacitance, great cyclic stability, good discharge and charge rates, and a high power/specific energy [49]. Aerogels are broadly classified into three categories based on their precursors and enhancements: inorganic, organic, and composite. Metal alkoxides and metal salts are converted into inorganic aerogels, which include metal oxide, chalcogenide, and metallic aerogels. Organic aerogels, on the other hand, are made from a variety of carbon-based sources, including biopolymers and phenol-formaldehyde resin, to form biopolymeric aerogels, carbon nanotubes, graphene aerogels, and other polymeric structures. On the other hand, the formation of composite aerogels, the third type of aerogels, requires the combination of both inorganic and organic precursors [50].

3.4. Fullerene

In 1985, F. Robert et al., discovered buckminsterfullerene (also known as fullerene or buckyball), the third carbon allotrope after graphite and diamond. This discovery marked the beginning of the field of carbon-based nanomaterials [51]. Fullerene is the only soluble molecule with a clear spherical molecular shape which is composed entirely of sp^2-hybridized carbon atoms. These compounds' distinctive zero-dimensional structures make them ideal building blocks for supramolecular assemblies and micro/nanofunctional materials utilized in optoelectronic devices, catalytic activity, medicines, and other applications [52]. Fullerenes are made up of variable numbers of carbon atoms, designated by n, which adhere to specified structural requirements. C_{60}, a well-known fullerene, is made up of 60 carbon atoms organized in a spherical cage with an approximate diameter of 0.7 nm. Because of its similarity to a soccer ball, C_{60} is sometimes known as a "buckyball". The C_{60} structure has two types of bonds composed of C–C with different lengths: C_5–C_5 single bonds within pentagons (0.145 nm) and C_5–C_6 double bonds within hexagons (0.140 nm) [53, 54].

Fullerene is now used in several chemical and material science applications, including electromechanical amplifiers, semiconductors, and polymers. Fullerene's small size, electron transport, antioxidant capabilities, photoactivity, hydrophobicity, and high reactivity, which permit structural alterations, are important attributes that have contributed to its evaluation [54]. It is a zero-dimensional hollow spherical nanoparticle that is utilized in high-tech applications and possesses exceptional structural and physical features among nanocarbons. Fullerene nanocomposites have been developed in a variety of ways. Fullerene molecules in modified or nanocomposite forms exhibit superior interactions, allowing hole, charge, or electron transportation through systems with significant efficiency [55].

3.5. Carbon nanotubes

CNTs, or carbon nanotubes, have been created and extensively explored since their discovery in 1991, owing to their fascinating and possibly valuable structural, electrical, and mechanical properties [56]. Hybrid supercapacitors with high power and energy densities composed

of metal oxide nanostructures and nanocarbon materials have been the subject of recent research. Because of its high specific surface area and advantageous electrical and mechanical characteristics, carbon nanotubes (CNTs) have been thoroughly investigated as potential electrodes for supercapacitors [57].

Because of its stability, electrical conductivity, and large area of surface, their use in conjunction with thin metal film electrodes has received a lot of attention in recent years [58]. Except for CNTs, which provide significant surface area benefits and allow non-faradaic energy storage, the majority of carbon-based supercapacitive materials with very large surface areas are incompatible with a structurally reinforced composite structure [59]. When a graphite sheet is twisted up into cylinders, it forms CNTs, which can be single-walled (SWCNT), double-walled (DWCNT), or multi-walled (MWCNT). It has a unique structure, a restricted size distribution in the nanoscale range, a large accessible surface area, low resistance, and Outstanding durability. These characteristics indicate that CNTs are appropriate materials for polarizable electrodes [56].

The utilization of CNTs' maximum surface area for continuous charge distribution is responsible for their great performance. Furthermore, their mesoporous features allow electrolytes to diffuse more freely, lowering the corresponding series resistance and so increasing power output. In recent years, it has received a lot of interest and has become a research hotspot. Related works investigated the production, normalization, and array of CNTs to produce CNT electrode materials with superior electrochemical characteristics [60]. Its superior conductivity, significant mesoporosity, and broad electrolytic accessibility all which contribute to a high charge transfer capability that makes it relevant [61]. Therefore, pure carbon nanotubes as capacitor electrode materials can only produce very moderate capacitance values, depending on their microtexture and catalyst impurities. It has been discovered that the capacitance increases with the number of defects in its outer walls. Better conditions for charge buildup are also provided by the thin coating of amorphous carbon on their walls. Furthermore, nanotube catalyst impurities may be the cause of redox reactions that result in pseudocapacitance effects. It can be perfect for supercapacitor applications as a conducting support for active materials such as conducting polymers and metallic oxides, as well as a significant component of carbon/carbon composites [62].

4. Activated carbon

Activated carbon (AC), often known as activated charcoal, is a rough, imperfect graphite. It contains a wide spectrum of pores of varying sizes, from obvious fractures and fissures to molecular diameters. Because of its huge surface area, AC is widely employed for a variety of applications, including pollution removal from air and water. Activated carbon has small, low-volume pores that improve the amount of surface region available for chemical treatments such as adsorption [63]. Activated carbon, with its porous structure and large surface area, provides a sustainable way to convert agricultural waste into useful items. This flexible material has a wide range of applications in industries such as the treatment of wastewater, air purification, medications, sensors, and storage systems for energy, thanks to its physicochemical attributes such as strong adsorption properties and high specific surface area [64]. About half of a supercapacitor's total material cost is made up of activated carbon. One major obstacle to entry for other carbons is the low cost of activated carbon electrodes made from biomass. The application of porous materials derived from biomass as electrodes has been studied recently [65]. With a remarkable surface area of 2696 m^2/g, the AC material made from rice husks showed a highly porous structure that is advantageous for energy storage applications. More active sites for electrochemical reactions are made available by this large surface area, which improves capacitor performance. At a temperature of 850 °C, the AC sample demonstrated the highest specific capacitance, measuring 147 F/g. A crucial factor in supercapacitors is specific capacitance, which indicates how much electric charge can be held per unit mass of the electrode material. Better energy storage capability is indicated by a larger capacitance.

Additional impedance study characterization revealed that the AC sample had a low resistance of 0.23 Ω. Low resistance ensures greater efficiency by lowering energy losses during cycles of charging and discharging. The supercapacitor electrode's frequency response was also assessed, and the results showed a quick response time of 0.11 s. The electrode is appropriate for high-power energy storage devices where quick charge-discharge cycles are needed because of its quick responsiveness, which shows how effectively it can store and release energy in dynamic applications [66]. The activated carbon has a BET surface area of 1,481 cm^2/g and a micropore volume of 0.0377 cm^3/g was obtained. The produced activated carbon had a capacitance of up to 114 F/g. Cotton stalks can create high-quality activated carbon electrodes for electric double-layer capacitors at a low cost [67]. To prepare activated carbon for EDLCs in organic electrolytes, straw was carbonized and activated with KOH. The inclusion of micropores and mesopores increased the specific area to 2316 square metre per gram might involve in high double-layer capacitance [68]. By using the $ZnCl_2$ activation process, activated carbon electrodes are made from the shell of Camellia oleifera, a biomass raw plant. Carbonization temperature and $ZnCl_2$ impregnation ratio significantly impact pore formation and electrochemical performance of the AC. Electrochemical studies demonstrate that activated carbon (AC-3-600) at 600 °C and 3 impregnation ratio exhibits the highest specific capacitance in 1 mol/L H_2SO_4 and 6 mol/L KOH electrolytes 0.2 A/g, respectively. The AC-3-600 has high capacitance due to its huge surface area, total pore volume, and high

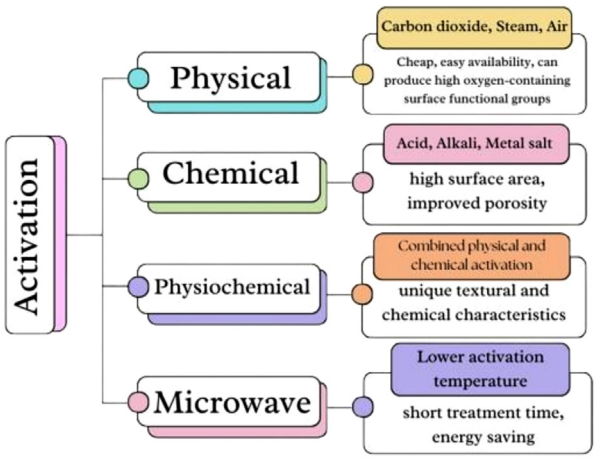

Figure 2. Diagrammatic representations of various methods for preparing activated carbon materials [70]

percentage of micropores [69]. The diagrammatic representations of various methods for preparing activated carbon materials are shown in Fig. 2.

4.1. Physical activation

Physical activation methods are extensively used in industry because of their low activating reagent costs (e.g., steam, CO_2, or air) and the absence of a requirement for further treatment and infrastructure [71]. Physical activation is the most typical procedure for producing activated carbon. This process occurs in two steps.

Carbonization is the initial stage in which the precursor material is pyrolyzed in an inert environment at moderate to high temperatures (300–800 °C). During this process, unstable bonds break, releasing volatile components such as persistent gasses and tars. This produces a carbon-rich residue known as char, which is distinguished by carbon aromatic rings and a basic porous structure. However, the initial porosity of the material has a low adsorption capacity because tars re-polymerize and condense on the surface during breakdown, clogging the pores. To solve this, an additional activation process is necessary to remove the tar deposits and increase adsorption capacity by extending the current porosity.

In the following stage, an activating agent is added, and the char is heated to a temperature of 700–1000 °C. During this process, the carbonaceous structure of the fuel develops a large porous structure and an increase in specific surface area when it is exposed to a reducing environment and passes through multiple heterogeneous reforming reactions that result in the char being partially gasified. The initial phase of the activation process involves removing tar deposits, opening primitive holes generated during pyrolysis, and forming new pores. After a long activation period, pore widening becomes the primary consequence, with pore deepening and fresh pore creation severely constrained. As a result, as activation time increases, the area of the BET and pore volume decreases, but additional meso and macropores form [72]. Compared to the chemical activation approach, the experimental conditions and simple apparatus are far more convenient and cost-effective. The advantages of this method include quick and easy activation, the capacity to prepare large amounts of activated carbon, and the availability and affordability of raw components. This strategy, however, makes it difficult to control the activation variables and the rate at which steam enters the chamber. During physical activation, numerous variables influence the electrical and optical properties, as well as the porosity of the holes. The quantity of raw material, the starting temperature, the distance within the sample and the first area of steam and argon gas entry, the carrier gas pressure, the pollution of the reactive environment, and the furnace's rate of temperature increase are some of the most effective variables in the production of porous carbon in this manner [73].

4.2. Chemical activation

The chemical activation method, which is more common, leads to more activated carbon at a lower temperature and pollutes the environment less than the physical activation method, which works best at high temperatures.

Table 1. Cyclic stability by achieving the activation temperature

Precursor	Activating reagents	Activation temperature (°C)	Cyclic stability	Reference
Onion husk	K_2CO_3	800	92.5% after 2000 cycles	[76]
Raw sugarcane Bagasse	K_2CO_3	650	98.63% up to 15,000 cycles	[77]
Coconut coir pith	NaOH	700	95.4% after 5000 cycles	[78]
Peanut shell	NaOH	450	98% 400 to 1000th cycle	[79]
Wheat husk/$NiCo_2S_4$	NaOH	400	88% after 5000 cycles	[80]
Spent coffee grounds	KOH	850	85% after 5000 cycles	[81]
Purple corncobs	KOH	700	76% after 50,000 cycles	[82]
Tamarindus indica	H_3PO_4	700	92.5% after 5000 cycles	[83]
Lemon peel	KOH	600	99.5% after 10,000 cycles	[84]

Chemical activation includes binding the material with an activator, followed by a heat treatment at temperatures ranging from 400 to 900 °C, which simultaneously carbonizes and activates the process of making activated carbon [74]. To activate carbon chemically, the following substances are utilized as activating reagents: K_2CO_3, Na_2CO_3, KOH, NaOH, $ZnCl_2$, and H_3PO_4 [75].

A study of the activated carbons' characteristics with other values published in the literature as listed in Table 1.

Among these, H_3PO_4 is an environmentally friendly activator that functions at a temperature of roughly 500 °C and can be restored much more quickly by only dissolving the saltiness of H_3PO_4 to preserve the well-developed mesoporous structure. H_3PO_4 catalyzes condensation and cyclization events in the precursors during the chemically activated process, improving bond clacking and speeding up cross-linking. The internal porous architecture may be preserved by the phosphate and polyphosphate esters forming a connecting layer, shielding the adsorbent from excessive burn-off [85].

4.3. Physiochemical activation

Activated porous carbon can be created through physical or chemical activation. The effects of physical and chemical activation on the properties and performance of activated porous carbon derived from various carbonaceous sources have been extensively researched. Their mutual influence, or the effect of physicochemical activation on the performance of activated porous carbon, is not clear and understudied [86]. Although it can produce high-quality activated carbon with a large surface area, physiochemical activation is greatly preferred even if it is more costly and time-consuming to make. Using oxidizing agents like carbon dioxide or steam and reducing agents like potassium hydroxide, zinc chloride, or phosphoric acid, this process usually takes place at high temperatures between 600 and 850 °C. These circumstances improve gasification, which adds to the end product's exceptional qualities [87]. Only a small amount of chemical activating agent is used in the process to produce narrow porosity, which is subsequently expanded through physical activation to produce well-developed porosity. The electrochemical performance was enhanced by biocarbon materials produced by combining physical and chemical activation techniques [88]. Using KOH and CO_2, Hu et al. suggested a physicochemical method for creating activated carbon from pistachio shells. They found that the surface area of specifically activated carbon increased when CO_2 based physical activation and chemical activation were combined, increasing the physical activation dimensions. The greatest specific surface area of 2145 m^2/g was obtained under the experimental conditions of KOH activation for 60 min, activation temperature of 780 °C, and CO_2 activation for 60 min. According to the study, when the activation period is at least half an hour, carbon materials produced by CO pyrolysis can attain optimal capacitive performance at a higher scan rate (300 mV/s). This resulted from the remarkably high percentage of mesopores in the activated carbon generated in such circumstances [89].

4.4. Microwave activation

Microwaves are electromagnetic waves made up of two perpendicular components: the electric field and the magnetic field. Microwave radiation is defined as electromagnetic radiation with wavelengths between 0.01 and 1 m and corresponding frequencies between 0.3 and 300 GHz. Typically, radar transmissions employ wavelengths between 0.01 to 0.25 m [90]. Among the many different kinds of materials that are outstanding microwave absorbents are compounds based on carbon. This trait allows carbonaceous materials to be transformed into new materials with distinct properties by heating them in a microwave. The temperature gradient in the microwave radiation approach gradually decreases from the sample's center to its surface because the interior of the sample is warmer than its exterior. This temperature differential easily releases the light components to create more holes. The following are additional advantages of microwave radiation over conventional heating methods: Selective heating, energy transfer instead of heat transfer, instantaneous starting and shutdown, fewer steps, lower activation temperature, improved safety, ease of use, smaller equipment dimensions, and less automation [91]. Direct activation is a one-step procedure for producing activated carbon that involves impregnation and heat treatment in a controlled environment. Significant biomass combustion is encouraged by a wide temperature differential between the hot exterior and the interior. A microwave system can be used to finish this operation, which takes less time than a two-step procedure. Microwave heating is preferred because traditional heating's high energy requirements and time commitment could make the activation procedure expensive [92].

5. Biowaste derived activated carbon

Researchers have recently concentrated on carbon-based electrodes that are sustainable and derived from biomass and its waste. The electrochemical properties of this biowaste-derived activated carbon are inferior to those of carbon fibers, conventional AC, and nanotubes made of carbon. Their main benefits, however, are their affordability, ease of production, environmental friendliness, and natural heteroatoms and functional groups, which make them an excellent alternative to carbonaceous materials derived from fossil fuels [93].

Animals, plants, coal, petroleum byproducts, and other raw materials including polymers and organic materials are some of the various sources of raw materials used to make activated carbon [94]. Many researchers have

Figure 3. Biowaste-derived activated carbon for supercapacitor applications

observed that activated carbon electrodes have a high capacitance of 200–300 F/g [95]. Meanwhile, biomass wastes have nanofiber structures with exceptional physical characteristics that enhance supercapacitor electrode performance [96]. The Fig. 3 shows that, the wide variety of agricultural and industrial waste are frequently used as AC precursors, such as coconut shells [97], hazelnut shell [98, 99], olive stone [99], corn cob [100], bamboo [101], rice husk [102], groundnut shell [103], pistachio-nut shell [104].

5.1. Activated carbon derived from coconut shell

The main constituents of coconut shell are lignin, cellulose, and hemicellulose. It grows in tropical and subtropical regions. Therefore, research into using coconut shells as a raw biomass material for synthesizing porous carbon substances has a lot of scope to grow [105]. Coconut shell-derived activated carbons have been widely used as electrodes, water and air purification adsorbents, and reduced graphene adsorbents. These activated carbons outperform other agricultural waste materials utilized as supercapacitor electrodes due to their large surface area, excellent conductivity, and hierarchical porosity [106]. The authors described a method used to generate high-performance, porous activated carbon material out of coconut shells, which are a plentiful and renewable resource in many impoverished nations. The synthesis combined pyrolysis and chemical activation by using potassium hydroxide (KOH) and sulfuric acid (H_2SO_4) in an acid-alkali activation process. Activated carbon electrodes with exceptional qualities, such as a notably high energy density of up to 600.89 F/g and a charge storage capacity of 46.94 Wh/kg, were generated using this novel technique. The electrodes also showed outstanding stability across numerous cycles of charging and discharging, which makes them viable options for energy storage applications. This study emphasizes the possibility of using a wealth of agricultural waste to create effective and sustainable materials for cutting-edge energy storage devices [107]. Activated carbon nanofibers (ACNFs) 25S, which are made from PVA, coconut shell charcoal, and a surfactant, have a high specific surface area (250.459 m^2/g) and exceptional energy storage capabilities, according to S.R.A. Sasono et al. These ACNFs demonstrate great promise as supercapacitor electrodes with a specific capacitance of 186.50 F/g, specific energy of 21.24 Wh/kg, and specific power of 373.01 kW/kg, underscoring the improved performance from adding activated carbon obtained from coconut shells [108].

5.2. Activated carbon derived from hazelnut shell

Hazelnut shell is one of the biomass wastes. It is used extensively in the production of AC due to its high reactive carbon content and low levels of ash, nitrogen, and sulfur. Furthermore, one of the most significant agricultural products is hazelnuts, which are found globally [109, 110]. When hazelnuts are processed, a lot of waste shells are created, most of which are utilized for heating. Because of this, using leftover hazelnut shell to make compounds with additional value can be a natural alternative resource and a way to increase value [110]. In their work, K. Al and S. Basakçılardan Kabakcı used hazelnut shells to separate the activated carbon. Hazelnut shell lignin and cellulose were fractionated by glycerol organosolv treatment. KOH was promptly combined in a 1:2 ratio with lignin, hazelnut shell, and cellulose-rich pulp. After that, each mixture was activated at 800 °C for an hour. The particular surface area, pore diameter, mi-

cropore volume, quantity of surface functional groups, and thermal properties of the various activated carbons varied. Because of its high specific surface area, large number of oxygen-rich surface functional groups, and pore diameter of more than 1 nm, hazelnut shell activated carbon is a great option for use as an electrode material [111]. Multi-layered graphene-like activated carbon was created via an easy sono-exfoliation method of chemically activated carbon from hazelnut shells. These electrodes were used in a flexible symmetric supercapacitor with a bio-polymer electrolyte based on hydroxyethyl cellulose. In contrast to the pre-exfoliated sample, structural analysis showed graphene-like structures within a porous carbon framework with fewer defects. With a specific capacitance retention of 46.7% in a 1 M Na_2SO_4 electrolyte and 77.8% after 10,000 cycles over 19 days, the material demonstrated exceptional electrochemical performance. Within a potential window of 0 to 1.6 V, it showed high energy and power densities of 36.2 Wh/kg and 199.7 W/kg, respectively. This demonstrates its promise for energy storage applications in flexible devices that are high-rate and long-lasting [112].

5.3. Activated carbon derived from peanut shell

Peanut shell, a clean, plentiful, affordable, and renewable biomass resource, is a by-product of peanut manufacturing, which yields about 7.44 million tons of peanuts annually worldwide. It can be utilized as feedstock to make carbon-based goods. In recent years, peanut shell has been used to create electrode materials for energy conversion and storage devices such metal-air batteries, lithium-ion batteries, and supercapacitors, as well as adsorbents that remove organic dyes and heavy metal ions from wastewater. Therefore, employing peanut shells as feedstock to develop a new carbon-based catalyst with remarkable performance and capacitive properties will be highly desirable. This will support ecological environmental preservation, waste reduction and reuse, and the sustainable development of society [113]. This work developed a simple process that combined hydrothermal treatment, $ZnCl_2$ activation, and pyrolysis to effectively produce hierarchical porous carbon from peanut shells. The specific surface area of the micropores, mesopores, and macropores that comprise the hierarchical structure (1549 m^2/g) is greater than that of the carbon, which was generated by direct calcination without $ZnCl_2$ activation (1069 m^2/g). The produced carbon exhibits good capacitive electrochemical performance as an electrode material for supercapacitors due to its wide specific area. The specific capacitance increased to 333 F/g at a current density of 0.5 A/g. The a-PnC demonstrated outstanding rate capability, holding onto 54.7% of its capacitance between 0.25 A/g and 50 A/g. Additionally, its capacitance dropped by just 4.7% after 10,000 cycles, suggesting exceptional stability for usage as an electrode material for supercapacitors. Its promise in supercapacitors is highlighted by the $ZnCl_2$ activated carbon made from peanut shells, which exhibits suited for high-power applications due to its simple manufacturing technique and exceptional capacitive performance [114].

5.4. Activated carbon derived from corn cob

Corn cobs are a common biomass waste from agriculture, with an estimated 28 million tons produced annually each year. Rich in cellulose, hemicellulose, lignin, and other functional groups, corncobs can be carbonized to produce highly valuable activated carbon. To improve biochar's adsorption capacity for organic dyes, the specific area of its surface and pore volume must be increased. The mass transfer rate and adsorption capacity of large organic dyes are reduced by biochar's absence of mesopores. Micropores, on the other hand, are primarily responsible for the adsorption of tiny molecules. Thus, hierarchically porous carbon has a lot of potential for adsorbing dyes. While mesopores are the primary transport channel for adsorbents and can adsorb large molecules, micropores have a good adsorption capacity for tiny molecules [115]. The author Shaoran Yang and Kaili Zhang, proposed a possible application for supercapacitors. The high BET surface area of 1471.4 m^2/g of the carbon compounds made from corncobs indicates their porosity. During electrochemical testing, the pyrolyzed-activated carbon electrode attains a specific capacitance of 299 F/g at a current density of 1 A/g. The supercapacitor device maintains 99.9% of its capacitance after 4,000 cycles, delivering an energy density of 20.15 Wh/kg at a power density of 500 W/kg [116]. Amorphous carbon with meso and microporous properties is created when carbon compounds generated from corncobs are chemically activated with KOH. The BET examination demonstrated the porous character of the carbon, while XRD proved its amorphous form. The development of micro- and mesoporosity in carbon generated from corncobs was validated by SEM and HRTEM investigations. At a current density of 0.5 A/g, the activated carbon in an aqueous three-electrode system reached a maximum specific capacitance of 390 F/g. It demonstrated a maximum specific capacitance of 164 F/g at 1 A/g in a two-electrode aqueous system. After only 10 s of charging at 0.5 A/g, a red LED was powered for more than 4 min using a symmetric supercapacitor with corncob carbon electrodes. This demonstrates activated corncob carbon's remarkable performance in supercapacitor applications. Bio-carbon-based electrodes are perfect for electrochemical energy storage systems since they are affordable, numerous, and eco-friendly [117, 118].

5.5. Activated carbon derived from bamboo

Bamboo, a tropical plant that grows widely throughout China, has been used extensively as scaffolding material in buildings. The process of turning bamboo scaffolding debris into air conditioners has garnered a lot of research interest [118]. Additionally, 90% of the mass of raw bamboo is composed of cellulose, hemicellulose, and

lignin, which make up 73.83%, 12.49%, and 10.15% of the mass, respectively. Pectin and a portion of aqueous extract are other minor ingredients. These elements are crucial because they give the electrode material high porosity carbon with a favorable pore combination. Moreover, cellulose-rich biomass can produce porous carbon with a nanomaterial structure, especially nanofibers. Furthermore, the fiber ingredient has a larger cell membrane and lumen than other plant fibers, especially those made from wood, which are typically smaller. Additionally, the structure of the nanomaterials in particular, the nanofibers helps to enhance the supercapacitor's performance [119]. Bamboo charcoal was converted into activated carbon by M. Jayachandran et al. utilizing chemical reaction techniques, and the physical and electrochemical characteristics of the resulting product were assessed in a range of aqueous electrolytes. The mixed electrolyte samples had a high specific capacitance of about 290 F/g at a current density of 1 ampere per gram. At 10 amperes per gram, the electrode material showed outstanding cyclic stability, holding onto 93% of its capacity after 1,000 cycles. For supercapacitor applications, mixed electrolytes are ideal because of their strong ionic conductivity [120]. Activated carbon for energy storage was created by K.M. Ajay and M.N. Dinesh utilizing biomass-specifically, bamboo-as a precursor. KOH was used as the activating agent in the chemical activation process to create the AC. With a carbonization temperature of 400 °C and an impregnation ratio of 1:2, the activation was carried out for two hours at 800 °C. The pore volume of the bamboo-activated carbon (BAC) was 0.6119 cm^3/g, and its surface area was 1273 m^2/g. While EDS verified an 88% carbon content, SEM investigation showed a tubular shape. Bamboo-activated carbon obtained an energy density of 1.1 Wh/kg, a power density of around 6.4 kW/kg, and a maximum specific capacitance of 143 F/g in a 1 M KOH electrolyte. The efficiency retention dropped to 70% after 25,000 cycles [121].

5.6. Activated carbon derived from rice husk

Rice Husk (RH) is essentially disposed of in the environment or utilized as a source of heat or nutrients for soil. RHs, however, can be transformed into useful materials and then released into the atmosphere. Together with 571 million tons of rice, 140 million tons of RH waste are created yearly. Mineral components and lignocellulose compounds make up the majority of RH. Moreover, silica is incorporated into the RH during development. Research has been done on using RH, a sustainable and renewable carbon supply, to create AC materials for a range of uses. To create valuable products, it is crucial to manage these inexpensive and plentiful raw materials properly. Even though several precursors have been used to produce AC, low-cost AC generation remains a difficult issue. As a result, using RH to produce AC can offer a more cost-effective alternative to more expensive synthetic approaches [122]. The resultant material exhibited an exceptionally high specific surface area (SSA) of 3292 m^2/g, as determined by BET analysis. Few-layer graphene was detected in the AGC composite's TEM and Raman spectra. At a scan rate of one millivolt per second, CV data revealed that the specific capacitance of pure AGC electrodes was 212 F/g. At a current density of 50 mA/g, GCD measurements showed a specific capacitance of 236 F/g. Using a straightforward chemical precipitation technique, different amounts of $Ni(OH)_2$ were precipitated onto the AGC surface. Both pure AGC and $Ni(OH)_2$-modified samples' surfaces were examined using SEM and nitrogen adsorption/desorption tests, which showed a noticeably porous surface structure. Theoretical concentrations of roughly 9 wt.% $Ni(OH)_2$ on AGC were found to provide the best specific capacitance findings. Based on the CV data, the specific capacitance of 9 wt.% $Ni(OH)_2$ on AGC electrodes was determined to be 258 F/g at a scanning rate of 1 mV/s. At a current density of 50 mA/g, GCD data showed a specific capacitance of 300 F/g, 22% higher than CV data and 27% higher when estimated using GCD data. The AGC electrodes upgraded with 9 wt.% $Ni(OH)_2$ were tested for up to 2000 charge-discharge cycles without losing their working qualities. Furthermore, during testing with up to 2000 charge-discharge cycles, the AGC electrodes upgraded with 9 wt.% $Ni(OH)_2$ displayed excellent structural integrity and stability. The above results were achieved using porous carbon, also known as activated carbon, which was effectively synthesized utilizing rice husk as a biodegradable waste [123].

5.7. Activated carbon derived from groundnut shell

Groundnut shells are the residual products after removing groundnut seeds from their pods. The vast majority of shells of groundnuts and skins are wasted, burned, or lost in the ground, resulting in ecological harm. However, new methods have emerged to put groundnut leftovers to good use. GNS is used in processes including the manufacture of nanocomposite and structural designs, as well as different commercial applications, is projected to minimize waste management costs, reduce environmental contamination, and thereby conserve the environment [124]. The high surface area-activated porous carbon electrode was created from bio-waste groundnut shells, which are a cheap and sustainable natural resource. Activated porous carbon was employed as supercapacitor electrodes with a high mass loading (9–10 mg/cm^2). Two aqueous electrolytes (6 M KOH and 0.5 M Na_2SO_4) were tested in a two-electrode system to evaluate the electrochemical performance of supercapacitor electrodes. Using 0.5 M Na_2SO_4 as the electrolyte, the supercapacitor electrodes showed enhanced energy and power density of 16.92 Wh/kg and 451.2 W/k, respectively. After 12,000 cycles of discharge at 0.5 A/g, the supercapacitor retained around 99% of its initial capacitance [125]. Ke Liang et al. used KOH activation and high-temperature carbonization to create highly efficient porous carbon made from peanut shell residue. With its

outstanding cycle stability, promising energy density, and high specific capacitance (575.7 F/g), the KOH-activated carbon (KOH-AC) provided an appropriate choice for biomass-based supercapacitors [126].

5.8. Activated carbon derived from pistachio-nut shell

Pistachio nut shells can be used for fuel for boilers or disposed of in graves. Because of the abundance of carbon and minor ash content, it was suggested that these abundant solid wastes be employed as raw materials for the production of activated carbons [127]. Pistachio shells contain 60.62% cellulose. Steam opens cellulose pores, allowing for the entry and adsorption of energy in tissue. Steam molecules play an important function in opening pores and expanding the surface area of those pores [128]. Pistachio-nut shells carbon that is activated is an attractive material for generating supercapacitor electrodes due to its excellent conductivity, affordable price, and high porosity. These features could improve the effectiveness of superconductors by enhancing mass transport, improving the area of the surface, and creating more acquisitive areas [129].

6. Future prospects and challenges

Carbon-based materials have demonstrated significant potential for supercapacitor applications, but there are still opportunities and difficulties to be solved. In the future, researchers hope to improve performance by customized porosity, heteroatom doping, structure, hybridization, and sustainable production methods. For example, developing carbon materials with optimum pore size and distribution can improve ion transport, but adding nitrogen, oxygen, or sulfur can increase electrical conductivity and capacitance. Furthermore, developing 1D, 2D, or 3D nanostructures can enhance surface area and ion accessibility. However, various issues must be addressed, including scalability, cost reduction, stability, and durability. Translating laboratory-scale synthesis into industrial manufacturing while retaining material quality remains a key challenge. Reduced production costs are also required to make carbon-based supercapacitors commercially viable. Moreover, long-term stability and resistance to damage, understanding ion-electrode interactions, and developing consistent testing methods are critical. Emerging trends have enormous potential, including graphene and 2D materials, carbon nanotube arrays, biomass-derived carbons, metal-organic framework-based carbons, and in-situ characterization approaches. Future studies should focus on the fundamental understanding of ion-electrode interactions, rational design of carbon materials, scalable synthesis methods, hybrid materials inquiry, and the development of new electrolytes and electrode topologies. By addressing these issues and investigating upcoming trends, researchers can realize the full potential of carbon-based composites used in highly efficient supercapacitors.

7. Conclusion

Materials made from carbon provide substantial prospects for developing supercapacitor technology because of its advantageous qualities, which include significant electrical conductivity, large surface area, and structural adaptability. This analysis focuses on several types of carbon materials – activated carbon from biowaste which provides unique benefits to energy storage. While activated carbon is inexpensive and widely available, nanostructured carbons such as graphene and CNTs provide increased electrical conductivity and energy density, addressing the rising demand for high-performance supercapacitors. However, challenges remain in achieving appropriate energy and power densities, sustainable and scalable synthesis, and improved cyclic stability for long-term usage. Recent advances in composite materials that blend carbon with polymers or metal oxides are promising, but perfect integration remains a technical challenge. Furthermore, the environmental impact of carbon production processes must be handled using green and renewable resources to support sustainable production practices. Ultimately, to close these gaps, more interdisciplinary research is needed, with an emphasis on affordable, environmentally friendly solutions that promote commercial scalability. Carbon-based supercapacitors have enormous potential for usage in electric automobiles, portable electronics, and green energy storage facilities, all of which will contribute to more effective and sustainable energy solutions.

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