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(REVIEW ARTICLE)

Recent advances in synthesis, characterization and energy storage performance of bio-engineered activated carbon for supercapacitors

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Abstract

With the growing demand for sustainable, high-performance energy storage solutions, research into bio-engineered activated carbon as an affordable and environmentally friendly supercapacitor electrode material has gained momentum. This review critically examines recent advances in the synthesis, characterization, and energy storage capabilities of bio-derived activated carbon. Advanced characterization techniques have provided valuable insights into the structural, chemical, and morphological properties of these materials. The review emphasizes the role of micro/mesoporous structures and surface functionalities in enhancing specific capacitance, energy density, and cycling stability. However, challenges such as scalability, consistency, and conductivity remain. Emerging strategies to address these issues, including material functionalization, hybrid electrode systems, and sustainable production methods, are explored. The review also discusses the future potential of bio-engineered activated carbon in next-generation energy storage devices, particularly flexible and wearable supercapacitors, highlighting its transformative role in advancing sustainable energy technologies.

Keywords: Bio-Engineered Activated Carbon; Supercapacitors; Biomass- Derived Materials; Energy Storage; Sustainable Electrode

1. Introduction

Research on bio-engineered activated carbon (BEAC), especially about supercapacitors, has increased due to the rising need for sustainable energy storage options. Supercapacitors, which are renowned for their extended cycle life and quick charge and discharge characteristics, are becoming more important in a range of applications, from huge grid storage systems to consumer devices. Concerns regarding environmental sustainability and carbon footprint are raised by the fact that traditional carbon materials used in supercapacitors frequently come from nonrenewable resources. In contrast, BEAC derived from agricultural and industrial waste materials, such as lignocellulosic biomass, offers a promising pathway to create environmentally friendly alternatives that are not only sustainable but also effective in energy storage applications.

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Rapid global economic growth in recent decades has raised energy consumption [1,2], and excessive reliance on fossil fuels has resulted in serious energy crises and environmental contamination. In this context, research into innovative and clean energy has received a lot of attention, and people have prioritized sustainable development [3,4]. In addition to energy storage and conversion technologies like solar cells, compressed hydrogen, fuel cells, supercapacitors, and batteries, several new sustainable energy sources have already been developed, including biomass, solar, wind, and tidal energy [5].Nowadays, scientists worldwide are concentrating on developing clean energy due to the scarcity of conventional energy and the worsening of environmental contamination. Electrochemical energy is a crucial component of this development. Since renewable energy cannot be transmitted, energy storage and renewable energy accumulation are crucial to its utilization [6]. The rapid population growth and continuous scientific and technological breakthroughs resulted in a significant increase in energy usage. Fossil fuels, which are unsustainable and have serious detrimental consequences on the environment and human health, provide the majority of the energy utilized today. Thus, bettering living conditions, raising environmental consciousness, and advancing scientific research will encourage the development and use of new clean and renewable energy sources.[7,8].Energy storage is an important aspect of energy utilization, hence researchers worldwide have been concentrating on ways to make energy storage systems more efficient [9]. Batteries, fuel cells, and supercapacitors are just a few of the energy conversion and storage technologies that have been developed during the past few decades [10]. Various types of batteries are currently the primary energy storage devices. Since they have been employed in many different industries, lithium-ion batteries have become the most efficient power source [11–13]. Double-layer capacitors are designed to store charge electrostatically by adsorbing ions to the electrode surface, while pseudocapacitors store energy electrochemically through rapid surface-controlled redox reactions [17,18].Due to their compact size and low weight, supercapacitors can be employed as power sources for computers, cell phones, and other portable devices in addition to being utilized in electric or hybrid cars [19]. Supercapacitors are primarily made up of double-layer capacitors (EDLC) and pseudocapacitors, both of which have characteristics that are strongly tied to the electrode materials. Transition metal oxide or sulfide is typically used as the active component in the electrode material for pseudocapacitors [20,21]. Nonetheless, porous carbon compounds are typically used in EDLC electrode materials [22].Carbon has been widely used in EDLC electrodes due to its many advantages, including its high conductivity, outstanding stability, and cost [23].Activated carbon [24,25], graphene [26], template carbon [27], carbon aerogel [28,29], carbide-derived carbon [30], and carbon nanotubes [31] are among the different carbon material electrodes that are now on the market. Because of its remarkable chemical stability, affordability, and huge specific surface area, activated carbon has been widely utilized in EDLC electrodes among various carbon-related materials [32]. However, the production process of many carbon compounds is quite complex, thus the employing biomass as raw materials to make carbon materials has been the research focus of many scientists [33,34]. Biomass has the merits of being a complete source, low cost, and renewable. Carbon sources for EDLC electrode materials are now derived from a variety of biomass types. Other than fossil fuels, biomass is a precursor of carbon material [35]. Plants or plant-based compounds that are produced in nature through the photosynthesis of carbon dioxide and water are primarily referred to as biomass. An estimated 80% of the carbon in biomass is found in plants on Earth, according to pertinent statistics [36].Through activation, high-temperature thermochemical conversion (pyrolysis), and other processes, biomass can be converted into activated carbon as a precursor of carbon compounds. It is possible to make solid charcoal, combustible gas, biological oil, and coke all at once. Activated carbon is widely used because of its many qualities, such as its large surface area, porous structure, and excellent chemical stability [37]. There are various benefits to using activated carbon generated from biomass as the electrode material for supercapacitors. (1) Compared to conventional techniques that use coal and petroleum, the production of activated carbon from biomass is easier and more economical. (2) Biomass is a plentiful and sustainable resource. (3) Activated carbon has stable chemical and physical characteristics. (4)Biomass-based activated carbon inherently possesses a hierarchical structure or porosity that facilitates efficient ion transport.(5) Large levels of nitrogen and phosphorus are commonly found in biomass materials, and these elements help the generated carbon create more active sites. Because of these advantages, biomass carbon compounds have a lot of promise for use as supercapacitor electrode materials. Because of their many benefits, including high specific energy, safety, low cost, and quick charge/discharge periods, supercapacitors are receiving more and more attention and development.Furthermore, bio-carbons represent a promising direction for supercapacitor electrode material development, offering substantial opportunities and potential. This review aims to focus on recent advancements in bio-carbons, including their synthesis, modifications, and characterization techniques.

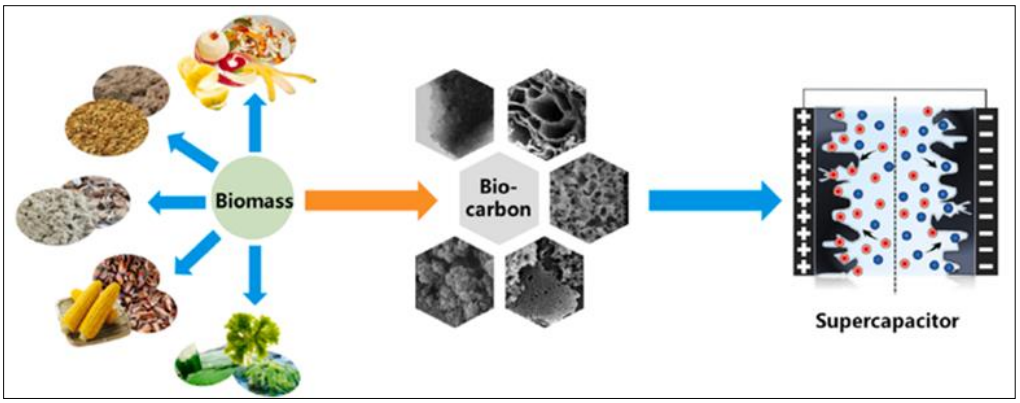

Figure 1 Bio-carbons as electrode for supercapacitors [89][90]

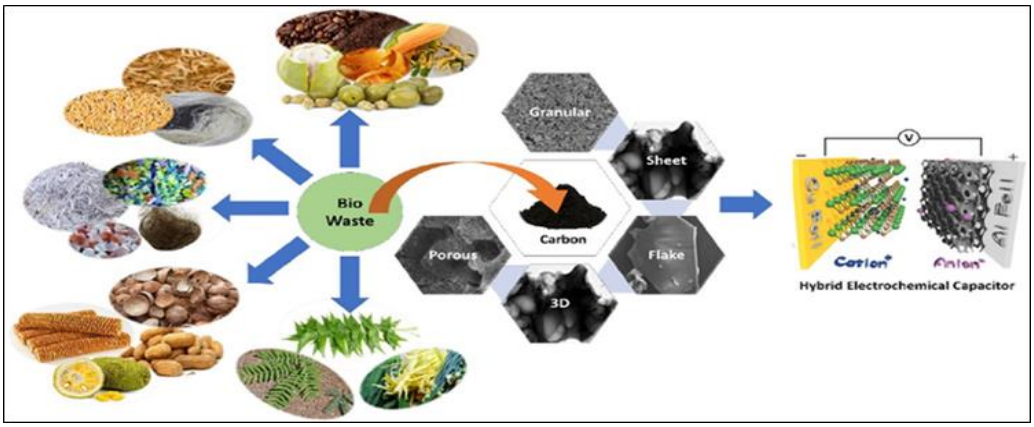

Figure 2 Bio-carbons as electrode for Hybrid Electrochemical supercapacitors [91]

2. Sources of Biomass

Cellulose, hemicellulose, and lignin make up the majority of plant biomass; cellulose is the most valuable of these due to its many uses, including the production of paper; hemicellulose is composed of heteropolymers of xylose and mannose monomers; lignin is a complex, three-dimensional polymer that is formed by the polymerization of phenylpropane with hydroxyl and methoxy substitutions; and cellulose and hemicellulose are used extensively in the production of paper, sugars, and biofuels [44–46]. Cellulose and many of its derivatives are environmentally friendly because they can be reintegrated into the environment through the action of decomposing microorganisms. Due mainly to the undervaluation of their economic worth, a significant amount of cellulosic materials produced by industrial and agricultural processes are currently wasted [47]. Despite being a plentiful and inexpensive resource, lignin is mainly unused. Though fewer than 2% of the lignin generated each year is recycled, it is a renewable precursor for a variety of value-added goods.15% to 40% of plants' dry weight is made up of lignin [48, 49]. It is essential for establishing a physical and chemical barrier against microbial attacks, improving cell wall cohesiveness, providing water resistance, and giving structural stiffness [50,51]. Currently, burning lignocellulosic materials to produce energy is the main use of these materials in agro-industrial activities. Although this application can lower expenses, lignin must be given more value. It is crucial to develop technology in order to fully utilize lignin's potential as a flexible raw material [48]. Studies have looked at turning lignin into artificial resins and surfactants, but it's also worthwhile to look into using it to make fine chemicals instead of those that come from petroleum. This would lessen pollution in the environment and the use of fossil fuels [48].The varied uses of lignin, its underlying chemistry, and the physicochemical changes it experiences during different processes should be the main topics of future research [49]. The essential element in lignocellulosic biomass that is in charge of adsorption has been found to be lignin [52]. Heat, steam, and synthetic fuels such oils, methane (CH_4), ethanol, biodiesel, methanol, and plant-based carbon are commonly produced from agricultural and agro-industrial wastes. One commonly used tactic to improve the sustainability of production operations is the conversion of trash into new materials [53–55]. A number of common agricultural crops and the wastes they produce are listed in Table 1. Understanding the yield or rate of waste generated per production unit is essential for effectively assessing or estimating the possible use of leftover biomass. According to Ajewole et al. [60], for example, 240 kg of dry beans and 506 kg of shells or dry pods are generated from a metric ton of freshly picked cocoa pods. As a result, there

is roughly 50% waste per ton and a 24% product yield per ton. According to White et al. [61], sugarcane crops generate 496.9 kg of residual biomass per hectare, which translates to 395 million tons of residues based on the world's total production area.Other studies indicate that the leftover biomass from sugarcane farming constitutes 15 to 25% of the overall production [62, 63]. In plantain agriculture, waste generation is estimated at 220 tons per hectare [64]. According to Subramaniam et al. [65], the oil palm business generates 13.55 tons of residual biomass per hectare annually. Furthermore, in the top producing nations, rice straw makes up 227.78 million tons, or 45%, of the entire amount of rice produced [66]. For every kilogram of product, 1.2 kilograms of waste are produced during the processing of soybeans, especially during the manufacturing of milk and tofu [67]. Likewise, 1 kilogram of residual coffee husk is produced for every kg of coffee [68].

Table 1 Crops in agriculture and waste products they produce [39, 42–45]

Agricultural Crop	**Waste Produced**
Cotton	Stems
Rice	Husk, straw
Oats	Grass, straw
Bamboo	Stems, leaves
Coffee	Husks, pulps
Sugarcane	Bagasse, molasses, cane trash, filter mud
Barley	Grass, shells, bran
Plum	Seeds
Coconut	Shells, fiber, copra
Jatropha	Shells
Maize	Cobs, stubble, stems, leaves
Peanuts	Shells
Apple	Pulp
Orange	Rinds
Nuts	Shells
Oil palm	Stems without fruits, fiber, shells
Potato	Shells
Pineapple	Shells and crown
Banana	Peels, pseudostem, rachis
Soy	Hulls, meal
Tobacco	Fallen leaves
Tomato	Leaves stems
Wheat	Grass, hulls, bran
Grapes	(vines) Seeds, stems

3. Synthesis of Bio-Engineered Activated carbon

According to Promdee et al. [69], the process of producing activated carbon (AC) is divided into three steps: a) pre-activation, which entails figuring out the necessary size and quality; b) activation, which transforms precursors into AC; and c) post-activation, which covers output parameters, quality control, and final AC characteristics. There are two primary ways to prepare AC: chemical and physical procedures. Physical treatments involve carbonizing the precursors initially, followed by activation in inert gas environments, such as carbon dioxide (CO_2), water vapor (H_2O), or nitrogen-

based compounds (N_2 or NH_3). On the other hand, chemical treatments entail heating the precursors in an inert atmosphere after impregnating them with a reagent [70]. In particular, the reactive agents aid in the development and growth of reticulated structures and pores [71,72] Commonly used chemical agents for this process include H_3PO_4, $ZnCl_2$, KOH, NaOH, H_2SO_4, CaO, and HF.

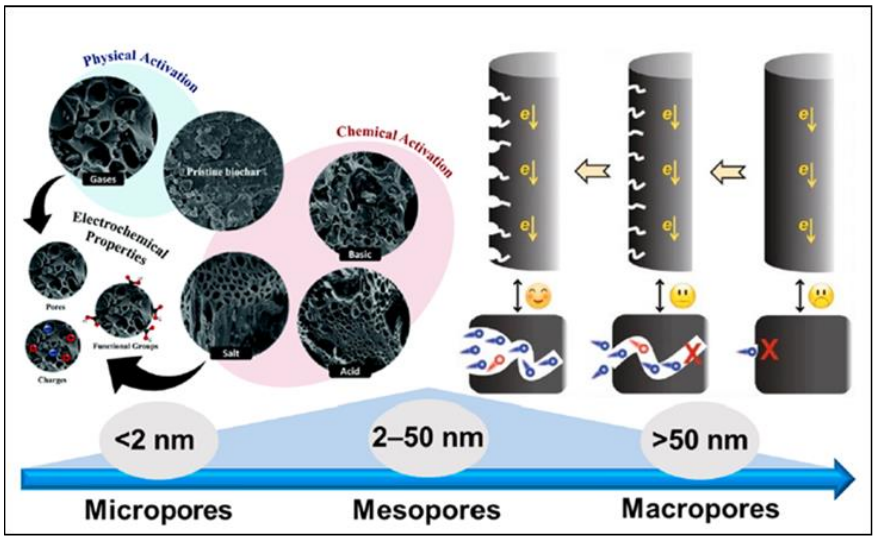

Figure 3 Influence of bio-carbon activation by physical and chemical processes [87,88]

3.1. Pyrolysis

By heating complex hydrocarbons with little to no oxygen present, a process known as pyrolysis transforms them into products with additional value. A carbonized solid (biochar), a liquid-phase product, and a non-condensable gas-phase product (CO, CO_2, CH_4, or H_2) are the three primary products that are produced when biomass is burned to temperatures between 300 and 800 °C [73,74]. Four types of pyrolysis can be distinguished depending on variables like temperature, residence duration, and heating rate (Table 2).

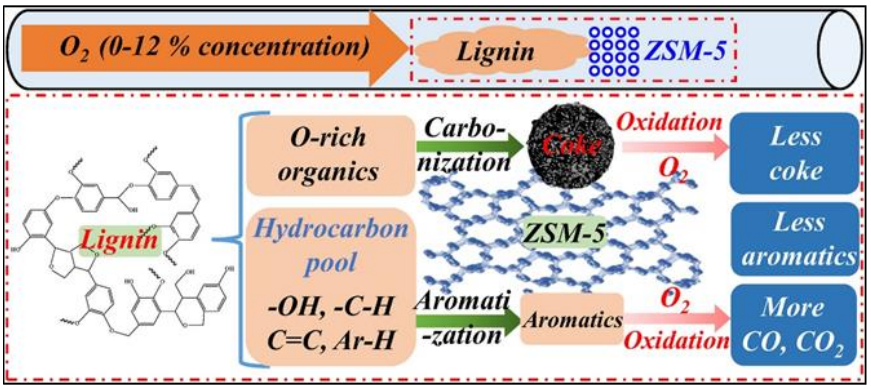

Figure 4 Reaction mechanism during the catalytic pyrolysis of lignin with ZSM-5 as catalyst in the presence of O2[118]

The components of biomass go through a number of reactions during thermal degradation, such as carbonization, fragmentation, rearrangement, condensation, dehydration, crosslinking, repolymerization, and depolymerization [76–78]. Slow pyrolysis is usually carried out under near-atmospheric pressure settings and produces products with a comparable composition by using longer residence times and slower heating rates [76]. Because it produces the most burned material, it is the most widely used method for making activated carbon (AC).

New approaches, including microwave-assisted pyrolysis, can generate hot spots in bulk materials and carbon particles, providing a viable way to generate AC at frequencies between 0.91 and 2.45 GHz [79].However, the carbonaceous product (biochar) derived from biomass thermal conversion under low or zero oxygen conditions generally has a less efficient surface structure compared to AC. Despite this, biochar is more cost-effective to produce than AC

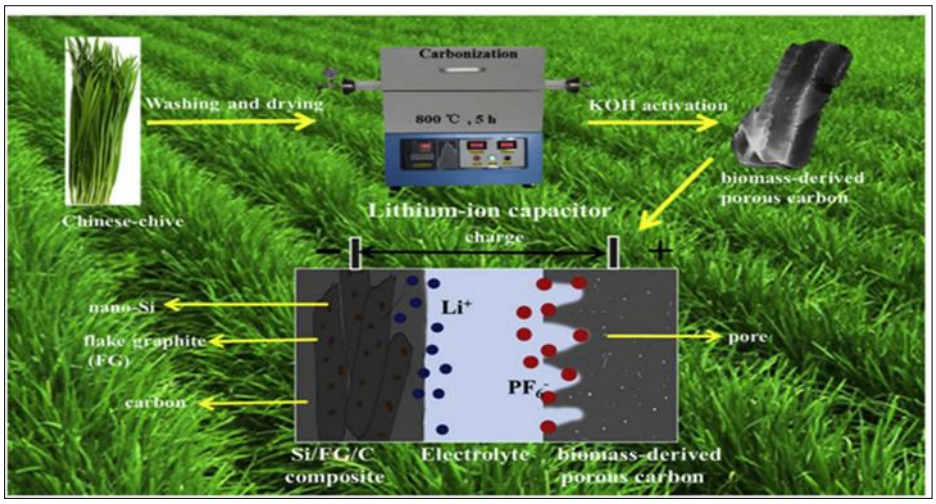

Figure 5 Chinese chives derived carbon for Li-HEC: Schematic illustration for synthesis procedure of CPAC and fabrication of Si/FG/C//CPAC hybrid LIC [119]

The carbonization process is described and divided into four temperature stages by Chen et al. [80]. With very minor structural alterations, physical desorption takes place in the first stage (25–150°C), eliminating about 12% of the absorbed water. The -H and -OH groups undergo intramolecular dehydration during the second stage (150–240°C). Significant amounts of tar, water (H2O), carbon monoxide (CO), and carbon dioxide (CO_2) are formed during the third stage (240–400°C), which is caused by the thermal breakage of glycosidic bonds, C-O bonds, and some C=C bonds by free radical reactions. A graphite-like structure with disordered layers that grow more aligned as the temperature rises starts to emerge in the fourth stage, which occurs above 700°C.

Table 2 Types, Conditions, and Products of Pyrolysis Methods [75, 76]

Pyrolysis Rate	Temp(°C)	Residence Time	Carbonized Product	Liquid (%by weight)	Gas (% by Weight)
Slow	300-700	Hours	35	30	35
Intermediate	500	10-20	20	50	30
Fast	800-1250	0.5-10	12	75	13
Flash	1050-1300	<0.5	20	50	30

3.2. Activation Mechanism

Since they have a direct effect on the performance of activated carbon (AC), porosity and selectivity are essential properties in both its manufacture and use. The degree of disarray in the monocrystalline structure, which is dependent on the kind of precursor, synthesis procedure, and activation technique used, affects these properties [81].

According to Pallarés et al. [86], the volatile component of the precursor (gases and tars) is released when the precursor is carbonized (at temperatures between 300 and 800 °C), which breaks less stable bonds. Because of the repolymerization of tars and their deposition on the material's surface, which might obstruct pores, the carbonaceous residues produced by this process are enriched with aromatic carbon rings, or plant carbon, and typically have a low adsorption capability. In order to eliminate these tar deposits and improve porosity and adsorption capacity, a post-activation procedure is necessary. The development and enhancement of AC's microporosity depend heavily on the activation process's temperature, duration, and activating chemicals [82].

High temperatures (700–1000°C) and the presence of an activating chemical are usually necessary for the activation process. Tar deposits are removed and new pores are formed, among other events that occur during this stage. The ideal temperature for AC adsorption is up for debate; higher temperatures are thought to improve adsorption by increasing porosity [82]. Nonetheless, some research indicates that while larger pores are often produced at higher temperatures, a larger pore volume is produced at lower combustion temperatures [83].

According to Pallarés et al. [63], longer activation times result in larger pores during activation, but they also decrease the depth of existing holes and the development of new ones. While pore volume declines, meso- and macropores form as activation times increase, and surface area (as determined by the BET technique) likewise rises [84].

AC's functionality and appropriateness for particular applications are directly impacted by the development and growth of porosity in its shape.

According to Qambrani et al. [76], mesopores are essential to liquid-solid adsorption processes, whereas micropores give activated carbon (AC) its high surface area and adsorption capacity. Conversely, macropores affect hydrological characteristics, solid-gas adsorption, and aeration. Significant changes in surface area, pore volume, and pore structure are brought about by physical activation, which is usually carried out with steam or gas. It also modifies surface chemical characteristics like polarity, hydrophobicity, and surface functional groups [85]. Better process control is made possible by the endothermic utilization of CO_2 and H_2O in the activation process. According to Ahmad et al. [83], CO_2 is especially useful for fostering microporosity in the initial phases of activation.

According to the findings of Pallarés et al. [86], CO_2 raised microporosity by 43%. Additionally, they found that the BET surface area decreased by 3% and the micropore volume decreased by 5.4% when high-temperature water (800°C) was used. However, because mesopores grew, the overall pore volume rose by 9.6%. Because mesopores expanded and contracted when the activation period was extended from one to two hours, microporosity decreased. In order to maximize the capabilities of AC, particularly when it is being customized for particular purposes, temperature and activation time are also essential considerations. As a result, the activation process alters the AC's chemical surface characteristics in addition to its form.

Important chemicals that improve adsorption capacity are created at each stage of synthesis, but temperature and time also affect how effective these compounds are. Cleaning the synthesized material is a crucial step in the manufacture of AC. The AC should be cleaned with water or alcohol if it has been chemically activated. Applying a vacuum devolatilization process at relatively low temperatures (between 100 and 250°C) and a pressure of -1 ATM is advised for physical activation. This procedure aids in the removal of contaminants that may result in pore saturation and, in certain situations, lower the adsorption capacity of the material.

4. Activated Carbon Characterization Techniques

Characterizing changes in the surface and structure of activated carbon (AC) is crucial to understanding its adsorption and absorption capacities, as well as its selectivity. Identifying the presence of new compounds formed during activation helps explain these properties. Various techniques can be used for characterization, depending on the available technology. These techniques can generally be classified into two categories: physical and chemical.

Physical techniques focus on evaluating the structure and morphology of AC, considering factors such as surface area, pore volume, and particle size. Below are the main physical techniques used to characterize AC.

4.1. Scanning Electron Microscope

One of the most popular tools for observing the surface morphology of different materials is the scanning electron microscope (SEM). A narrow electron beam is scanned across the sample to create SEM pictures, which are then measured and spatially mapped. With resolutions of 50–100 nm, this method enables magnifications between 10 and 50 kX [92]. Depending on the electron source, SEM can be categorized as either thermal or field emission, and it can function in high vacuum or ambient pressure environments. In order to attain better resolution, which can reach up to 5 nm, samples must be coated with thin metal coatings, such as platinum or gold, when working with materials that have high electron absorption capabilities [115].

The application of SEM to the analysis of carbonized coffee husk samples was emphasized by Ronix et al. [93]. In contrast to the stiff and compact morphology of the precursor samples, which showed no discernible cavities or pore structure, they saw the formation of porosity, with cavities of various sizes and distributions on the surfaces. The surface and pore structures of activated carbon (AC) can be effectively characterized by SEM. To see the surface morphology of materials with strong electron absorption capabilities, the samples must be coated with gold [115]. Even though SEM is frequently utilized, finer details can be obtained with higher resolution methods like atomic force microscopy (AFM) or scanning probe microscopy (SPM). Both methods have been used to characterize black carbon, with AFM achieving resolutions of 1-2 nm and SPM exposing structures at a size of 5-10 nm [94].

4.2. Raman Spectroscopy

By measuring photon scattering energy, Raman spectroscopy (RS) is a potent method for determining and examining the structural properties of functional groups on activated carbon (AC) surfaces. This method involves exposing AC to monochromatic laser light. RS depends on the inelastic scattering of photons, even though some of the light is elastically scattered. The molecules may change between various vibrational or rotational states as the sample and laser interact [97, 98].

Wave number, or cm^{-1}, is a measure of the energy differential between incident and reflected beams and relates to molecular vibrations in the adsorbent. As a result, the chemical species included in the sample can be identified [99–102]. Minimal spectrum manipulation, straightforward data interpretation, high spectral recording speed, great spatial resolution, and relative ease of sample preparation are only a few benefits of Raman spectroscopy. As a useful adjunct to infrared spectroscopy, it also makes it possible to identify surface species simultaneously and clearly without being hampered by water [103,104].

Nevertheless, there are certain restrictions on RS. The sample may be impacted by degradation effects including fluorescence and sub-development, which could result in inaccurate or partial data interpretations [116].

4.3. X-ray Photoelectron Spectroscopy

A popular method for measuring and describing the elemental composition, chemical state, and oxidation states of the elements and radicals found on the surface structures of activated carbon (AC) is X-ray photoelectron spectroscopy (XPS). Surface chemistry research relies heavily on XPS, also referred to as electronic spectroscopy for chemical investigation [117, 105–107]. This technique involves exposing the material to X-ray radiation and measuring the electrons that are released. The method examines the kinetic energy of the material's upper (0 nm) and lower (10 nm) regions [116].

The XPS procedure was broken down into three steps by Susi et al. [165]: (1) When X-ray photons are absorbed, energy is transferred to an electron in the nucleus of an atom. (2) An empty core state is left behind when certain atomic species are stimulated, releasing photoelectrons. (3) Using an electron analyzer, the energy content of the released photoelectrons is determined after they pass to the material's surface before departing.

When using XPS to detect, measure, and investigate doping group binding, sample preparation must be taken into consideration. To avoid drawing the wrong assumptions regarding the composition of the material, this includes taking into account the intrinsic photoemission response and the existence of pertinent spectra. During the analysis, special attention must be paid to allocating binding energies to the appropriate atomic configurations [116].

AC made from the husks of Jatropha Curcas was subjected to XRD examination by Tong Poothorn et al. [108]. They found that the structure was primarily amorphous, with broad peaks and no acute peaks. Broad peaks at 26° and 43° were also observed, suggesting the development of a crystalline carbonaceous structure akin to the alignment of graphene layers. The structural alterations in cellulose (from grass) and lignin (from wood) during AC production at various temperatures were investigated by Keiluweit et al. [109]. According to their XRD data, the crystallinity of cellulose chars breaks down and becomes random between 300 and 400°C. A transition to a more organized structure is indicated by the formation of turbostratic crystallites above 400°C. The quality of these analyses has also been improved by advanced XPS variations such as analysis near the X-ray absorption edge (ECBARX) and extended fine X-ray absorption spectroscopy (EFRX).

4.4. Fourier Transformed Infrared Spectroscopy

A light beam at different frequencies is passed through a sample using the Fourier-transform infrared spectroscopy (FTIR) technique to determine the transmittance or absorbance of infrared light [110,111]. Infrared density (either transmittance or absorbance) is plotted against wave number (cm^{-1}) in the generated spectra. FTIR has many benefits, including high sensitivity, a good signal-to-noise ratio, high-quality spectra, non-destructiveness, the ability to detect species at low concentrations, and the ability to analyze multiple gas species at once.

However, because dipole-moment compounds absorb infrared photons, FTIR works best with these compounds. FTIR cannot be used to analyze compounds lacking a dipole moment because they do not interact with infrared light [112, 113].

Because absorption bands do not always match to certain functional groups, errors may occur during quantitative evaluation and infrared spectrum interpretation. Rather, these bands might be the consequence of several bands that reflect various functional groupings overlapping. Furthermore, problems such irregular light scattering brought on by the large adsorbent particle size, poor transmission, and sample preparation challenges might make it difficult to acquire reliable infrared spectra from activated carbon (AC) [116,114].

5. Conclusion and outlook

As society continues to develop, increasing attention is being given to environmental pollution and energy shortages. In response to these challenges, as well as the growing demand for energy and the rapidly evolving fields of electrical and electronics markets, significant efforts have been directed towards enhancing energy storage, conversion, and rapid transportation technologies.

One promising solution that has gained considerable attention in recent decades is the supercapacitor, an emerging type of energy storage device. The electrode material for supercapacitors is primarily activated carbon (AC), which is capable of storing electric energy quickly. However, the conventional raw material for AC production is coal, a non-renewable resource. This has led to increased research into using biomass as a raw material for AC, as it offers a renewable, sustainable alternative. Biomass waste, when used to produce activated carbon, addresses both waste disposal concerns and the high costs and complex processes associated with traditional AC production.

As a naturally occurring, plant-based material, biomass offers several advantages, including wide availability, renewability, and an eco-friendly nature. These characteristics, combined with the low cost and sustainability of biomass, make it an attractive option for the development of bio-carbon materials, particularly for use in supercapacitors. This review has explored the recent progress in utilizing bio-carbons as electrode materials for supercapacitors. It has also examined the various sources of biomass, and the processes involved in preparing bio-carbons, such as carbonization and activation, as well as the different activation methods.

The electrochemical properties of bio-carbons, including specific capacitance, cycle life, and energy/power density, are influenced by factors such as heteroatomic doping, specific surface area, and pore structure. While significant research progress has been made in the field of bio-carbons, several challenges remain. One of the most pressing concerns is the cost of producing activated carbon. In future research, it is crucial not only to focus on improving the performance of electrode materials but also to consider their economic feasibility. Moreover, ensuring a stable and reliable supply of biomass raw materials remains a key issue. Establishing standardized and efficient biomass collection systems will be critical to meeting production demands.

Another challenge is the variability in carbonization methods. It is important to develop a universal method based on the inherent characteristics of biomass to ensure the consistent quality of biochar produced from various biomass sources. Additionally, attention must be paid to the potential emission of harmful gases (e.g., NO_2, SO_2) during the activation process, and appropriate measures should be taken to mitigate these risks.

Further innovation in the synthesis of porous carbon materials capable of storing large amounts of charge is needed, alongside improvements in the working temperature range, lifespan, and self-discharge rate of electrode materials. Addressing these issues will significantly enhance the performance and cost-effectiveness of bio-carbon materials for supercapacitors.

Despite the challenges, the numerous advantages of bio-carbons make them a promising solution for the future. By improving energy consumption structures, bio-carbons can play a key role in the transition toward cleaner economic development globally.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors have no known personal conflicts of interest.

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