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REVIEW **Open Access**

Supercapacitor electrodes based on biowaste

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Abstract
This study presents a compelling overview of biowaste as a valuable, carbon-rich material for electrode components in supercapacitors. Easily sourced from local environments, biowaste offers numerous advantages that make it an appealing choice for sustainable energy solutions. We have carefully compiled a list of biowaste materials that can be converted into high-performance electrode materials, providing detailed information on specific capacitances, power and energy densities, voltage windows, and cycling stability. The innovative extraction of activated carbon from biowaste represents a challenging yet highly promising approach for creating carbon-based electrodes. Carbon contributes significantly to enhancing the efficiency and performance of energy storage devices. With a diverse array of biowaste materials readily available, substantial efforts are being made to transform these resources into valuable carbon-based materials through various synthesis techniques discussed in this study. Our research rigorously assesses the effectiveness of activated carbon derived from different waste sources, demonstrating its potential as a supercapacitor with impressive specific capacitance and power density metrics. Adopting biowaste solutions can help shape a cleaner and more efficient energy future.

1 Introduction

The need for more efficient and versatile energy storage solutions to capture excess energy from renewable sources such as wind and solar is increasingly evident [1, 2]. According to Gogotsi et al. [2], to have well-developed hybrid and electric vehicles or, in other words, to have a successfully adopted renewable energy source, there is a need to have available and suitable energy storage systems. The comparison of the power and energy density performance of standard energy storage devices such as batteries, supercapacitors, fuel cells, and capacitors can be well understood by the Ragone plot as in Fig. 1, which also identifies users to select the most appropriate device to use according to their needs. Among various energy storage technologies, supercapacitors are particularly notable for their capacity to deliver and absorb energy quickly, characterized by high power density and long cycle life [1, 3]. After the development of the first supercapacitor in 1957 by General Electric, a lot of different commercial supercapacitors were launched [1].

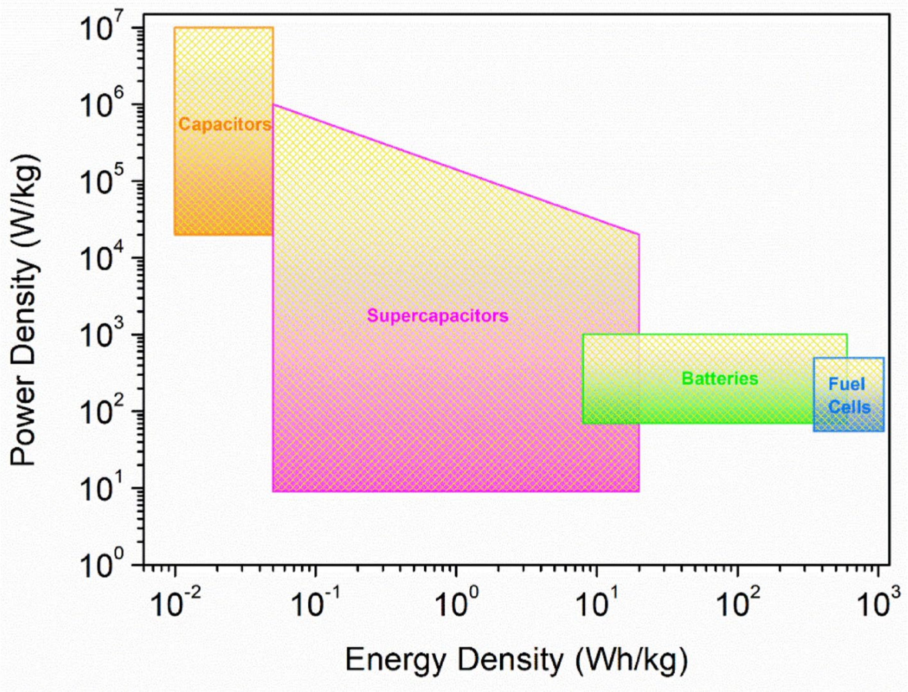

Fig. 1 Ragone plot showing power and energy density comparison for various energy storage devices

2 Supercapacitors

The growing energy demands of modern civilizations highlight the urgent need for advanced energy storage solutions. Supercapacitors, with their ability to deliver high power, rapid charging, and excellent long-term cycling performance, have become increasingly prominent in a wide range of applications, such as electric transportation systems (buses and trains), elevators, wind energy systems, robotic vacuum cleaners, and uninterruptible power supply (UPS) units [4, 5]. Aside from that, supercapacitors are safer than batteries and have low maintenance costs [6]. Therefore, supercapacitors, in other words, electrochemical capacitors (ECs) or ultracapacitors, can be used in various applications such as electric vehicles, memory backups in information systems, and power supplies. Also, compared to batteries, supercapacitors can work at higher temperatures [1, 7]. Supercapacitors have a long cycle life of almost 500,000 cycles, which is high compared to batteries because of their charge transfer mechanisms. Since supercapacitors do not have a charge storage mechanism governed by dominant chemical reactions, as in batteries, supercapacitors can endure high charge and discharge cycles [1, 3, 8–12].

2.1 Charge storage mechanism of supercapacitors

Supercapacitor charge storage mechanisms are classified into three main types: electric double-layer capacitors (EDLCs), pseudocapacitors, and hybrid supercapacitors, as in Fig. 2 [1, 11]. In EDLC type supercapacitors, charge storage occurs through the formation of a Helmholtz double layer at the electrode–electrolyte interface. This process is driven by the adsorption and desorption of ions, resulting in high power density and excellent cycle stability [1, 3, 6, 11, 13–15]. The EDLC supercapacitors provide higher energy density than traditional capacitors because of their electrode surface area and

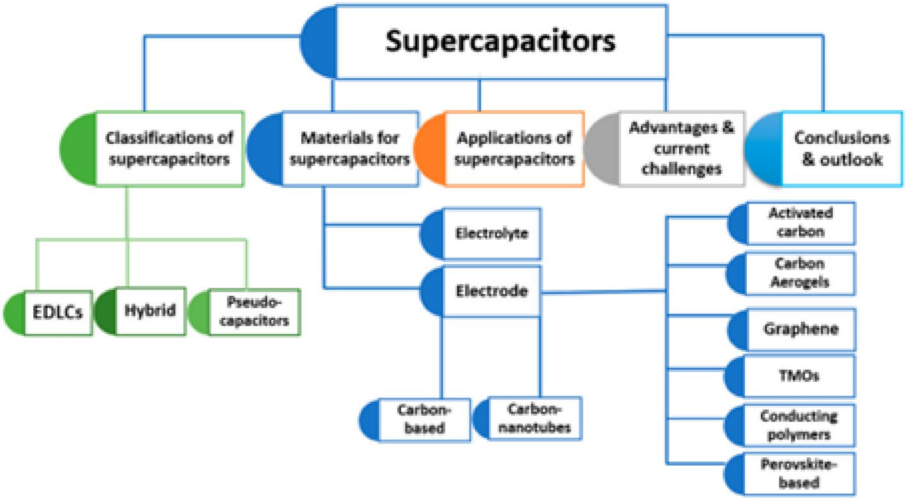

Fig. 2 The types of supercapacitors are classified based on charge transfer mechanisms. Reprinted from An Overview of the Emerging Technologies and Composite Materials for Supercapacitors in Energy Storage Applications, Adedoja et al. [18].

smaller charge separation distance [1, 13]. The electrochemical performance is affected by several parameters, such as the size of the electrode surface and the thickness of the formed Helmholtz layer. Due to the high porous morphology of carbon materials and their derivatives, such as graphene, graphite, carbon nanotubes (CNTs), and activated carbon, and their large surface area that is 500–4000 m^2g^{-1}, outstanding electrical conductivity, their usage as an electrode material is highly preferable in EDLC types in supercapacitors [1, 13, 14, 16, 17]. In pseudo capacitors, the charge is stored via Faradaic redox reactions of the electroactive species on the electrode and higher energy densities are achieved with a short cycle life [1, 6, 13–15, 17]. In contrast, hybrid supercapacitors combine both EDLC and pseudocapacitive charge storage mechanisms, integrating the advantages of each to enhance overall performance [1].

2.2 Carbon-based materials as electrode materials

Carbon-based materials are prevalent since they are easily accessible, non-toxic, highly chemically stable, and can be used in an expanded temperature range [1, 9, 13, 14, 18]. Carbon materials are also chemically stable in acidic and basic solutions [18]. Over the past decade, carbon has emerged as one of the most widely utilized active electrode materials in both supercapacitors and fuel cells [6, 19]. Carbon materials having mesopores and micropores generally provide high energy densities in EDLC [20]. The crucial factor for achieving high capacitance lies in the use of conductive electrodes with a high specific surface area that effectively block ion penetration while facilitating charge storage [7]. Among carbon materials, activated carbons (ACs) are among the most used carbon materials as electrodes in supercapacitors due to their low cost, simple synthesis route, and high surface area [2, 11, 13, 14, 17, 20]. Activated carbons (ACs) are produced from carbon-rich precursors through a process known as carbonization, which involves heat treatment in an inert atmosphere. This is typically followed by selective oxidation using activating agents such as CO_2, KOH, or water vapor to develop the porous structure [2]. There is significant interest in utilizing biowaste materials for supercapacitor applications, as illustrated in Fig. 3.

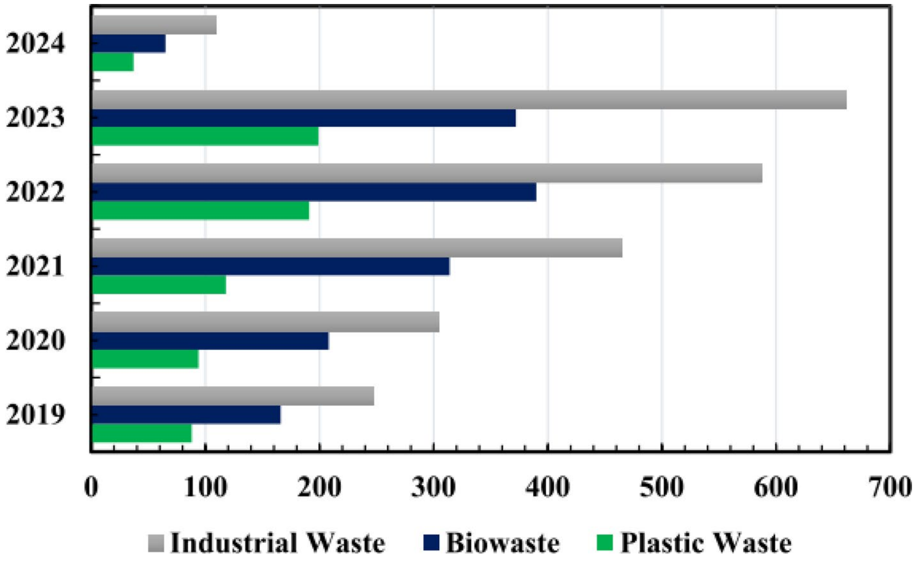

Fig. 3 The number of research studies based on the use of biowastes in supercapacitors [21]

In this paper, we aim to review the biowaste materials that can be used as carbon-rich precursors in synthesizing activated carbons as electrode material in supercapacitors. Therefore, a brief review is provided based on activated carbons and the synthesis methods that can be applied, and the potentially activated carbons derived from biowastes that can enhance the supercapacitors are given in a detailed table.

3 Activated carbon (AC)

ACs gained attention due to their high porosity and large surface areas [1, 9, 14, 16, 17]. One of the popular activated carbons stems from the capacitive charge storage and is processed at the micropores (<2 nm), which may hinder the movement of electrolyte ions due to tiny size of the pores and can prevent the electrolyte ions from reaching the whole electrode/electrolyte interface [6]. The ineffective mismatch of the pore size versus the electrolyte ions can lead to low specific capacitance and energy density values [22]. Therefore, there is a need to control the pore size, structure, and the ratio of the mesopores to micropores [1]. Surface area and porosity are widely acknowledged as two essential factors that directly impact the energy storage performance of synthesized carbon nanostructures.

Although bio-derived carbons typically exhibit high surface areas, their supercapacitive performance is often hindered by insufficient porosity. Limited research has been reported on the systematic tuning of porosity in these materials, despite its significant role in enhancing the efficiency of energy storage devices such as supercapacitors [23]. There is a wide range of application areas for using porous carbons, including water desalination methods, energy storage applications, use as a catalyst, and gas separation membranes [24]. Recently, there has been a higher number of research based on synthesizing AC based on waste materials such as plant, animal, industrial, and household to alter the need for fossil fuels, reducing the toxicity and environmentally hazardous properties of fossil fuels and lead a more circular economy as summarized in Fig. 4 [1, 9, 14–16].

Fig. 4 The representation of biowastes that can be used as carbon-rich precursors that can be used to derive activated carbon with their advantages as electrode material in supercapacitors

3.1 Porous characteristics of different forms of activated carbon

These pores are categorized into three groups based on size: micropores (diameter < 2 nm), mesopores (diameter between 2 nm and 50 nm), and macropores (diameter > 50 nm). Porous characteristics refer to the size, distribution, and arrangement of pores within a material, typically ranging from 2 to 50 nanometers in diameter. Various carbon materials, including activated carbon (AC), graphite, and carbon nanotubes (CNTs), exhibit distinct mesoporous features that play a significant role in determining their properties and overall performance in different applications.AC is renowned for its hierarchical porous structure, which is responsible for its exceptionally high surface area and is composed of interconnected pores varying in size from large to small. The exact distribution of pores within AC depends on raw materials and the activation process employed. Rough estimations suggest that most of these pores fall within the micropore category (60–90%), followed by mesopores and a minority of macropores [2]. The properties of AC, including its adsorption capabilities and overall device performance, are primarily determined by micropores. Hence, maximizing the micropore surface area to enhance the formation of Helmholtz double layers at the interface level increases capacitance. Porosity also directly correlates with the applied voltage of AC, causing pores to expand or contract and thus influencing material adsorption [25]. Additionally, to extend the potential window of AC, metal oxides and polymers are incorporated to broaden the voltage range of the supercapacitor [26, 27]. While this enhances both capacitance and voltage, it results in a pseudo supercapacitor, where double layers form and faradaic reactions occur. This situation combines the attributes of electric double-layer formation and redox reactions at the electrode surface. Yildirim et al. explored how metal oxides and activated carbon-based electrodes contribute significantly to achieving the highest power densities [28]. One technique to optimize the energy density in a supercapacitor involves creating a ‘mass-balanced cell. Each electrode’s capacitance and potential limits must be measured separately to maximize the performance of the supercapacitor. Even when constructing a symmetrical supercapacitor with electrodes of the same material, it must be corrected to assume that each electrode operates similarly. This can result in potential asymmetry at each electrode, even if built with the same material [29].

3.2 Activated carbon synthesis methods

Several carbonization techniques, such as pyrolysis and hydrothermal carbonization, can be employed to convert waste materials into carbon, often in conjunction with chemical or physical activation methods, as illustrated in Fig. 5. These methods significantly influence the final electrode properties and the electrochemical performance of supercapacitors [14, 16]. Pyrolysis involves thermally decomposing biowaste in an inert atmosphere at elevated temperatures. The pyrolysis temperature is crucial in determining the carbon structure and surface area. Higher temperatures increase carbonization and graphitization, enhancing conductivity, but excessively high temperatures can reduce surface area due to volatile matter loss and pore collapse [11, 15]. During pyrolysis, biowaste materials are heated to elevated temperatures in an oxygen-free environment, typically under an inert gas such as nitrogen (N_2) or argon (Ar). This process promotes the thermal decomposition of organic components and the release of volatile compounds, resulting in the formation of a carbon-rich residue known as "char" or "biochar." [11].

Hydrothermal Carbonization involves heating biowaste in water at elevated temperatures and pressures, producing hydrochar, a carbon-rich material with lower carbonization than pyrolysis. This method is advantageous for biowaste with high moisture content, avoiding pre-drying. The hydrothermal method is performed at very high

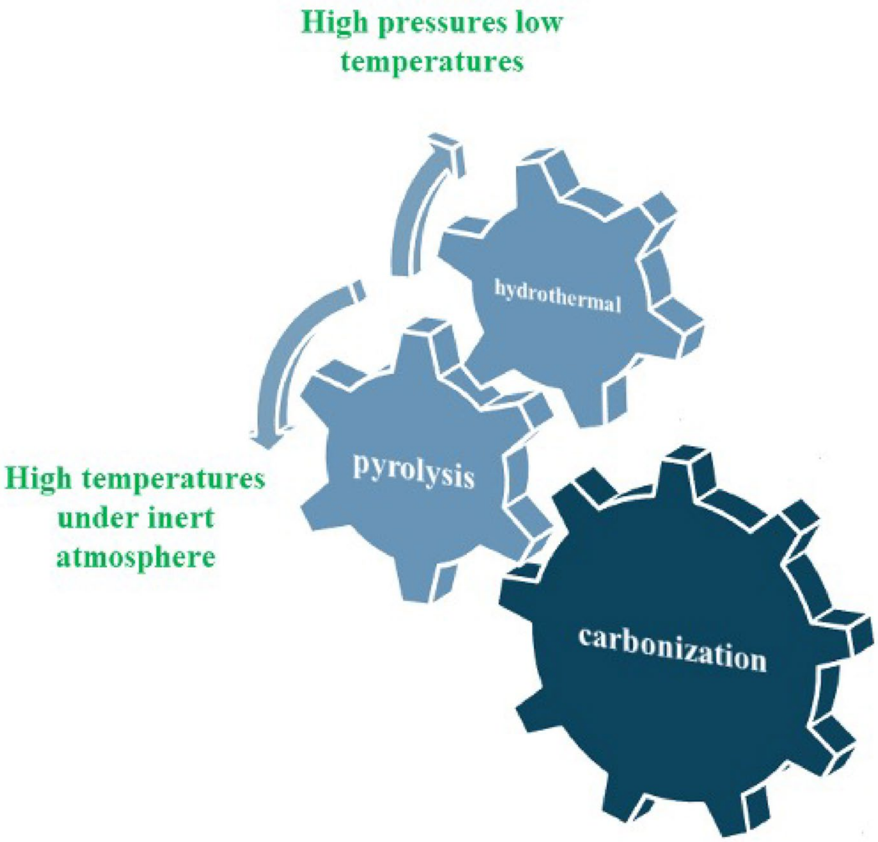

Fig. 5 The schematic shows two main carbonization methods

pressure, originally done in a hydrothermal reactor vessel which is kept at high pressure via air-tight screws. In principle, the hydrothermal autoclave is heated to a temperature close to 200 °C with water. The hydrothermal method is primarily selected if a specific end-structure is asked [11]. There are one-step and two-step carbonization methods, where several steps propose high-temperature carbonization, pre-carbonization, and activation processes, respectively. According to the selected activation process, the sizes of the pores can be tuned and have a prominent effect on the electrochemical properties [11, 15]. It is important to note that extended activation times and higher temperatures tend to increase the average pore size of the resulting carbon material.

[2]. During the pre-carbonization process, a low-temperature heat treatment from 300 to 700 °C is applied to biowaste material to eliminate any thermal shock effect and reduce defects [15]. On the other hand, the high-temperature carbonization process increases the electrode density but conversely decreases the specific surface area. Activation enhances porosity and surface area.

3.2.1 Activation procedures of AC

The activation methods can be classified under four, but in the literature, it's mainly classified as two main activation methods: physical and chemical, as given in Fig. 6 [30].

Physical Activation In physical activation, the pre-carbonized biowaste is thermally treated at temperatures between 400 and 1100 °C, followed by exposure to activating gases such as CO_2, air, or steam to enhance porosity and develop the material's surface structure [11, 15]. It is important to note that activation with air and steam should be avoided at high temperatures, as it may lead to structural degradation. In contrast, CO_2 is considered the most suitable activating agent for physical activation, as it enables controlled activation even at elevated temperatures around 800 °C. However, unlike chemical activation methods, physical activation offers limited control over pore size distribution [15]. For example, in [31], physical activation was conducted using a quartz reactor operated at 700, 750, and 800 °C. In this procedure, 20 g of the precursor material were placed inside the reactor, with nitrogen gas flowing continuously to serve as a carrier and to create an inert atmosphere. This nitrogen flow is critical as it prevents oxidation and ensures that the activation process is purely physical rather than chemical. Once the reactor reached the desired temperature, deionized water was introduced into

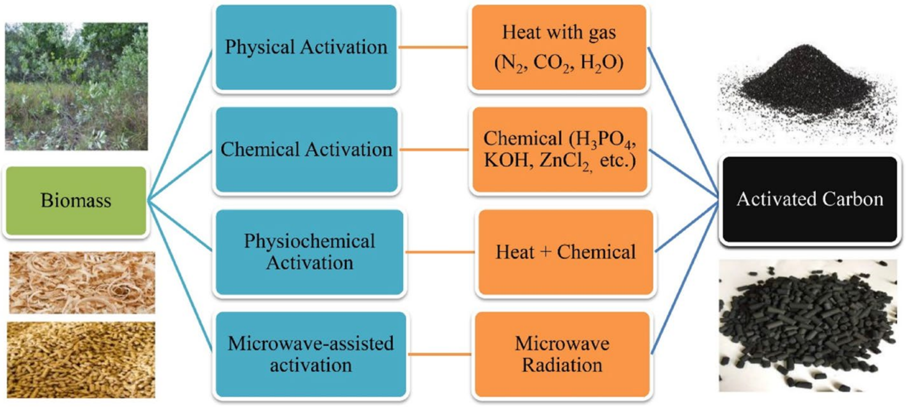

Fig. 6 The activation methods can be classified into four categories, but in the literature, there are two main activation methods: physical and chemical [29]

the system. This was accomplished using a peristaltic pump, which precisely controlled the flow rate of the water to match the nitrogen flow. Introducing water vapor at high temperatures facilitates the physical activation process by promoting the formation of pores within the precursor material. This steam activation was maintained for 60 min, allowing sufficient time to develop the desired porosity and surface characteristics in the activated material.

Chemical Activation Chemical activation has several advantages compared to physical activation methods, like assuring short activation time, high specific surface area, higher yield, and comparably low temperatures [15]. Different chemical activation agents are available, such as potassium hydroxide (KOH),sodium hydroxide (NaOH), zinc chloride ($ZnCl_2$),and phosphoric acid (H_3PO_4) [11, 15, 32]. KOH is one of the most used chemical activation agents, and its activation mechanism is described in the chemical reaction below.

$$6\mathrm{KOH} + 2\mathrm{C} \rightarrow 2\mathrm{K} + 3\mathrm{H}_2 + 2\mathrm{K}_2\mathrm{CO}_3 \tag{1}$$

In principle, during the activation process, the KOH is reduced to free metals such as potassium (K^+) and intercalates into the carbon network, leading to the carbon network expanding at relatively high temperatures. Free metals can be removed destructively and lead to the generation of graphitic layers in the carbon network, creating micropores [15]. For instance, a chemical activation was performed on 1 g of spent coffee grounds (SCG-P) by combining them with KOH in a 1:1.5 weight ratio. The resulting mixture was thoroughly homogenized and then placed into alumina crucibles. These crucibles were subjected to chemical activation in a tubular furnace, where the process was conducted under a nitrogen atmosphere to ensure an inert environment. The activation took place at two distinct temperatures, 775 and 850 °C, for 30 min. After heating, the activated material was allowed to cool down to room temperature. The resulting solid was then meticulously washed several times with water to remove any residual chemicals, continuing this rinsing process until it reached a neutral pH, indicating that the material was free of excess KOH. This step is crucial for ensuring the activated carbon is suitable for further applications. This method demonstrates a practical approach to recycling waste materials, such as spent coffee grounds, into valuable activated carbon, which can be used in various applications, including adsorption, catalysis, and energy storage. Using KOH as an activating agent, combined with precise temperature control, plays a critical role in enhancing the porosity and surface area of the final product, thereby improving its effectiveness in these applications [31]. The choice of synthesis and activation methods should be carefully considered based on the specific requirements of the supercapacitor application. For example, high surface area and specific capacitance may favor physical activation, while better pore size control and higher power density may favor chemical activation. For instance, in a study [33], cucumber peel is used as a biowaste precursor and carbonized and chemically activated. The carbonization and activation process has been depicted in Fig. 7 for clarification of the protocols.

Despite of KOH, there are a variety of other chemical agents that can be used. For example, in a study potassium carbonate (K_2CO_3) is used as a chemical agent as in Fig. 8 [34].

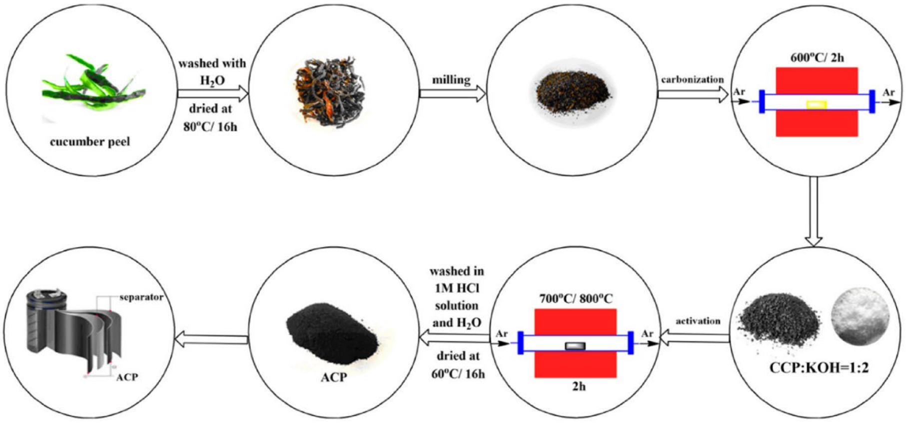

Fig. 7 The illustration of the synthesis protocol of AC from cucumber peel [33]

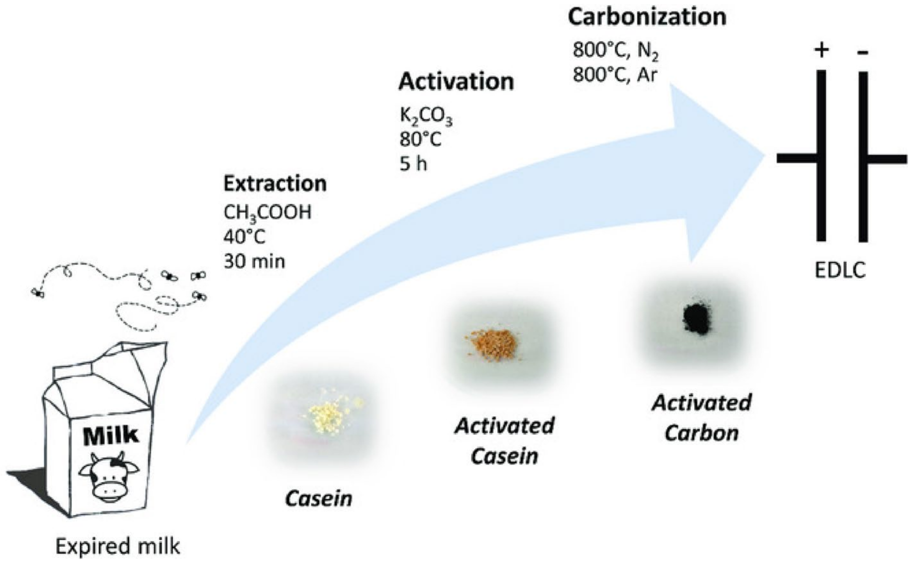

Fig. 8 The synthesis of AC from expired milk [34]

3.3 Novel applications and future directions

The diverse nature of biowaste allows for tailoring the properties of derived activated carbons to suit specific applications. For example, the high surface area and hierarchical pore structure of activated carbon derived from fruit peels make it suitable for applications in portable electronics, where high energy and power densities are crucial. In contrast, the robust and mechanically strong activated carbon obtained from agricultural waste like coconut shells can be employed in electric vehicles, where high power delivery and long cycle life are essential. Furthermore, industrial byproducts can be utilized in grid-scale energy storage systems after appropriate pre-treatment and activation, where cost-effectiveness and long-term stability are paramount. Emerging research focuses on enhancing the performance of biowaste-derived supercapacitors through various strategies. Novel activation techniques, such as microwave-assisted activation, offer faster processing times and improved control over pore structure. Surface modifications, including heteroatom doping and the incorporation of metal oxides or conducting polymers, can significantly enhance the electrochemical activity and stability of the electrodes. The development of hybrid materials, combining biowaste-derived carbon with other electroactive materials like metal–organic frameworks, offers synergistic effects that can boost the overall performance of supercapacitors. These developments open new avenues for creating efficient and environmentally friendly energy storage systems using biowaste-derived materials.

3.4 Use of bio-based waste materials as carbon precursors

Developing carbon materials suitable for EDLCs requires careful selection of active material sources. Although raw materials account for only a small portion of total AC production costs (approximately 1.3–2.9%, depending on the process), using abundant and locally available resources offers clear benefits for sustainable and cost-effective production [35, 36]. Biowaste contains various biopolymers, with cellulose, hemicellulose, and lignin among the primary components (Fig. 5). Given the increasing trends in food processing and agricultural production, they are ideal carbon sources. However, the biopolymers within these constituents must be disassembled to create porous carbon structures. In contrast, due to its impure composition, sewage is considered a less favorable source. Mass-produced biowaste is generally more reliable in terms of purity. Cellulose and hemicellulose are more prone to decomposition because of their hydroxyl groups and lower degree of polymerization compared to lignin.Most food waste predominantly comprises higher proportions of cellulose and hemicellulose than lignin. Pyrolysis of cellulose and hemicellulose occurs at lower temperatures than that of lignin. During the decomposition of these biopolymers, small hydroxyl groups such as CO, CO_2, and H_2O are released, forming interconnected porous structures. This process results in the creation of micropores and establishes a 3D hierarchical porous structure.

Given that most food processing, agricultural waste, and industrial plant waste share a similar composition of lignocellulose, their porous structures' size and 3D network resemble one another. This interconnected porous structure facilitates rapid electrolyte diffusion and enables efficient adsorption of molecules, making it conducive for applications such as electrode material in supercapacitors.

Raw biowaste often contains impurities such as heavy metals, inorganic salts, and various organic compounds, which can adversely affect the electrochemical performance of the resulting materials. Therefore, thorough pre-treatment and purification processes are essential to produce high-quality activated carbon. The relative content of cellulose, hemicellulose, and lignin in the biowaste significantly affects the characteristics of the final carbon product. Cellulose and hemicellulose, being mainly linear polymers with hydroxyl groups, decompose at relatively lower temperatures during pyrolysis. This decomposition promotes the development of micropores and increases surface area—an important factor for achieving high specific capacitance in supercapacitors, as it enhances the number of active sites available for ion adsorption. However, the resulting carbon can be less graphitic and have lower electrical conductivity. Lignin, on the other hand, is a complex, cross-linked polymer with aromatic rings, providing structural rigidity. Its decomposition requires higher temperatures and leads to a more graphitic carbon structure with higher electrical conductivity, which is advantageous for efficient charge transport within the electrode. However, the resulting porosity and surface area are typically lower compared to cellulose- and hemicellulose-derived carbons. Therefore, the ideal biowaste source for supercapacitor electrodes would have a balanced composition of cellulose, hemicellulose, and lignin to achieve a desirable combination of high surface area, good electrical conductivity, and suitable pore size distribution. For example, a biowaste source rich in cellulose and hemicellulose might yield activated carbon with high specific capacitance but lower power density due to limited ion transport. Conversely, a lignin-rich biowaste might produce electrodes with higher power density but lower specific capacitance due to the lower surface area. The optimal balance depends on the specific requirements of the supercapacitor application. During decomposition and dehydration condensation reactions, micropores are formed as a result. Lignin, on the other hand, possesses a different structure. It contains aromatic rings and is known for its sturdy, nonporous nature. Lignin typically yields less than cellulose and hemicellulose, requiring higher temperatures and harsher conditions for longer durations during the activation process. The application of heat during treatment causes the decomposition of biomass, resulting in the loss of mass and water content, along with a decrease in its biopolymer composition. Carbonization and activation processes contribute to forming hierarchical porous structures in biowaste. The adjustments during these processes determine the proportion of micro, meso, and macropores in the resulting material. To gain insight into the surface area of processed biowaste samples, measuring the BET (Brunauer–Emmett–Teller) surface area is essential. The proportions of different pores can be determined by assessing the adsorption of molecules of varying sizes. This aspect could be explored further in future studies. Understanding the structure of lignocellulose is paramount as it enables the tailored creation of porous carbon materials with desired proportions for efficient adsorption [37].

Bamboo is one of the highly popular biowastes, and the number of researches using bamboo increased over the years as in Fig. 9 [38]. It is important to note that bamboo properties are age-dependent, as reported by Azeez and Orege [39], the cellulose content decreases with increasing bamboo age.

3.5 Biowaste enhanced supercapacitors

Biowaste-enhanced supercapacitors represent an energy storage device that utilizes materials derived from biowaste and offers several potential advantages, including reduced costs and enhanced sustainability compared to traditional supercapacitor electrodes made from synthetic materials. Moreover, biowaste-enhanced supercapacitors can leverage biowaste-derived electrolytes, further improving the sustainability of these devices. The properties of carbon materials can be tuned not only by precursors, porosity, etc., but also with the heteroatoms involved [40, 41]. Heteroatom doping is a very efficient way to improve the specific capacitance of carbon materials [13, 41]. Via heteroatom doping using electroactive species, pseudocapacitive behavior is adopted in the material [19, 41]. Therefore, heteroatom doping of the carbon materials' capacitive properties can be enhanced [6]. By the insertion of heteroatoms such as N_2, boron (B), and phosphorus (P) into the carbon matrix, pseudo-capacitive behavior can be induced and used as a way for boosting the ion diffusion on the surface of the electrodes [10]. The most used heteroatoms are oxygen and nitrogen [40, 41]. Animal bones, a significant form of biowaste generated in large volumes, hold great potential for energy-related applications. Their rich content of P, N, calcium (Ca), and sulfur (S) makes them an excellent source of heteroatoms for the synthesis of in-situ doped porous carbon materials [42, 43]. Al Haj and Mousavihashemi et al. used cellulose nanocrystals

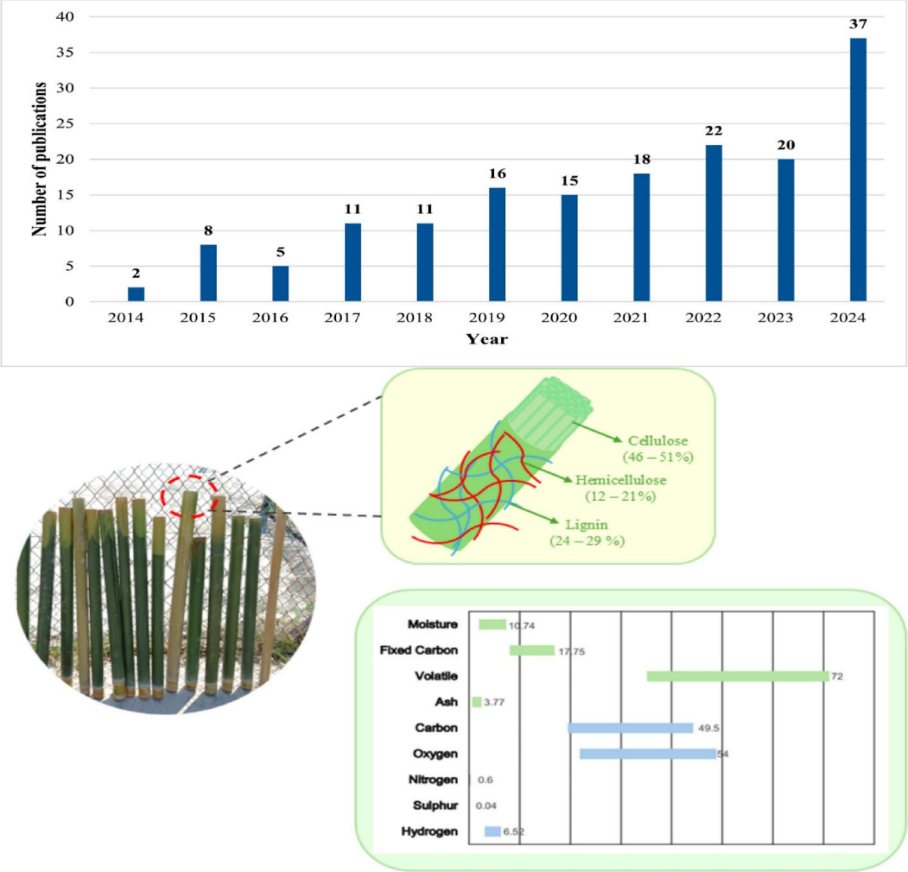

Fig. 9 The number of researches that published yearly based on bamboo and the content of bamboo [38]

(CNC) obtained from brewery waste and cross-linked with aluminum ions to form a transparent hydrogel electrolyte and used animal bone biowaste to use as an electrode and implemented a flexible symmetric supercapacitor (PC//Al-CNC//PC), which demonstrates impressive energy and power densities, as well as excellent cycling stability. The device also shows strong mechanical durability under repeated bending, making it a promising candidate for sustainable energy storage applications. Figure 10 shows the synthesis protocol of the proposed supercapacitor. The animal bones have been carbonized at 900 °C for 2 h after crushed and activated using HCl at 900 °C for 1 h, and used as ink in the supercapacitor. The electrochemical performance during bending has been investigated using CV technique as in Fig. 10a below. All CV curves displayed consistent behavior with minimal loss in capacitance after the device was returned to its original position. GCD and EIS results supported the CV findings, showing negligible changes at different bending angles, which confirms the excellent mechanical stability of the PC//Al-CNC//PC device. At a 90° bend, the specific capacitance slightly increased by less than 0.1%, likely due to reduced electrolyte thickness, which shortens ion transport paths and enhances ionic conductivity. The fitted equivalent circuit model showed an increase in double layer capacitance (CPE2-T) and a decrease in bulk resistance (R_b) at 90°. This supports this explanation; after straightening, R_b increased, but performance remained stable. These findings highlight that the supercapacitor, entirely derived from biowaste, offers outstanding electrochemical performance along with benefits such as low cost, non-toxicity, and environmental sustainability, making it highly promising for use in

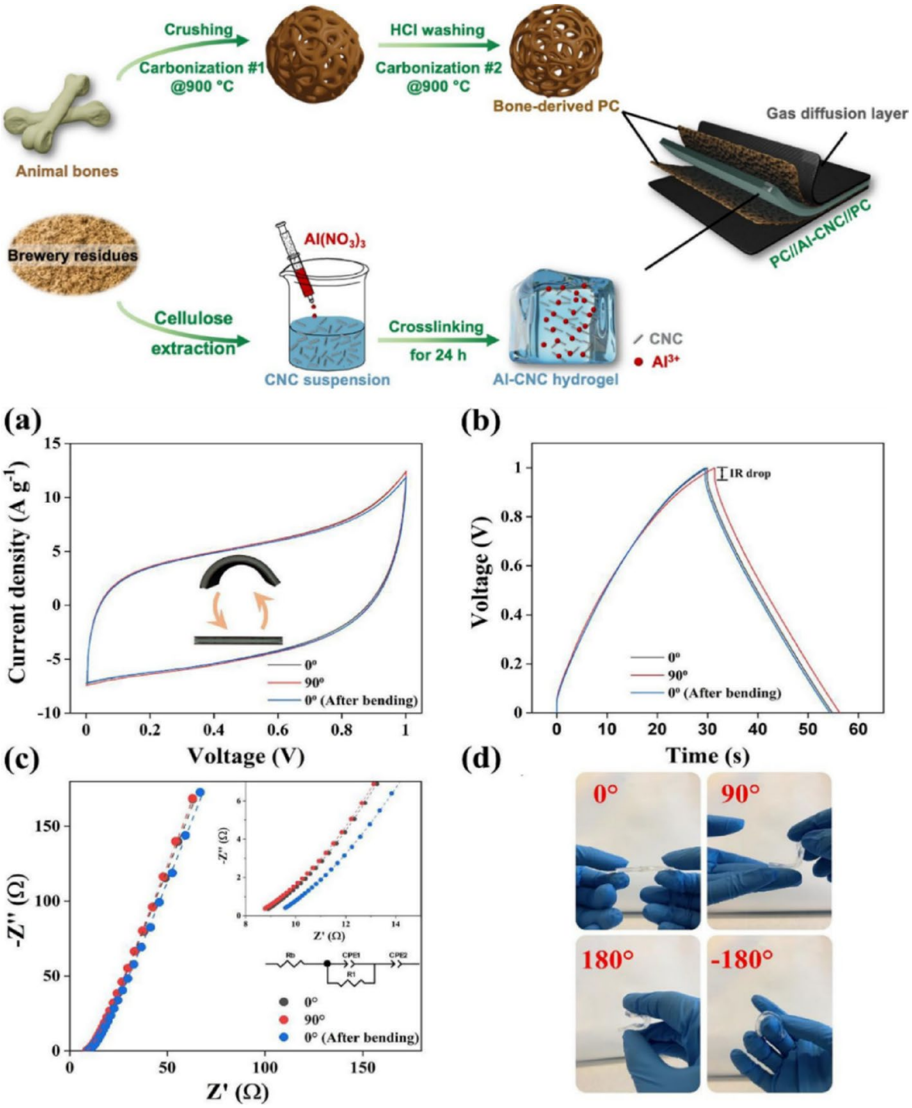

Fig. 10 The Synthesis protocol of the proposed flexible supercapacitor showing the electrode and electrolyte preparation and the Electrochemical Analysis Investigation of the cell's electrochemical performance under bending conditions includes: **a** CV measured at a scan rate of 50 mVs^{-1}; **b** GCD at a current density of 5 Ag^{-1}; **c** EIS, with the inset displaying the equivalent circuit model; and **d** images of the Al-CNC hydrogel subjected to different bending angles (0°, 90°, 180°, and − 180°) [42]

wearable electronics. A novel, low-cost, scalable, and single-step approach is explored to synthesize nitrogen-doped porous carbon nanomaterials with three distinct morphologies, utilizing different parts of the Bombax malabaricum biowaste as carbon precursors as in Fig. 11. In summary, three distinct nitrogen-doped porous carbon nanomaterials (N-HGNS, N-HPC, and N-CMF) were synthesized from different parts of Bombax malabaricum biowaste via a simple carbonization and self-activation process as in Fig. 10. Variations in inherent organic (C, N) and inorganic (K, Na, P, Cl$^-$) content led to distinct microstructures and electrochemical behaviors. Among them, N-HGNS-900 exhibited superior performance due to its wrinkled graphene-like morphology, high conductivity, and enhanced ion transport. These results highlight the effectiveness of biowaste-derived hierarchical porous carbons for high-performance energy storage applications.

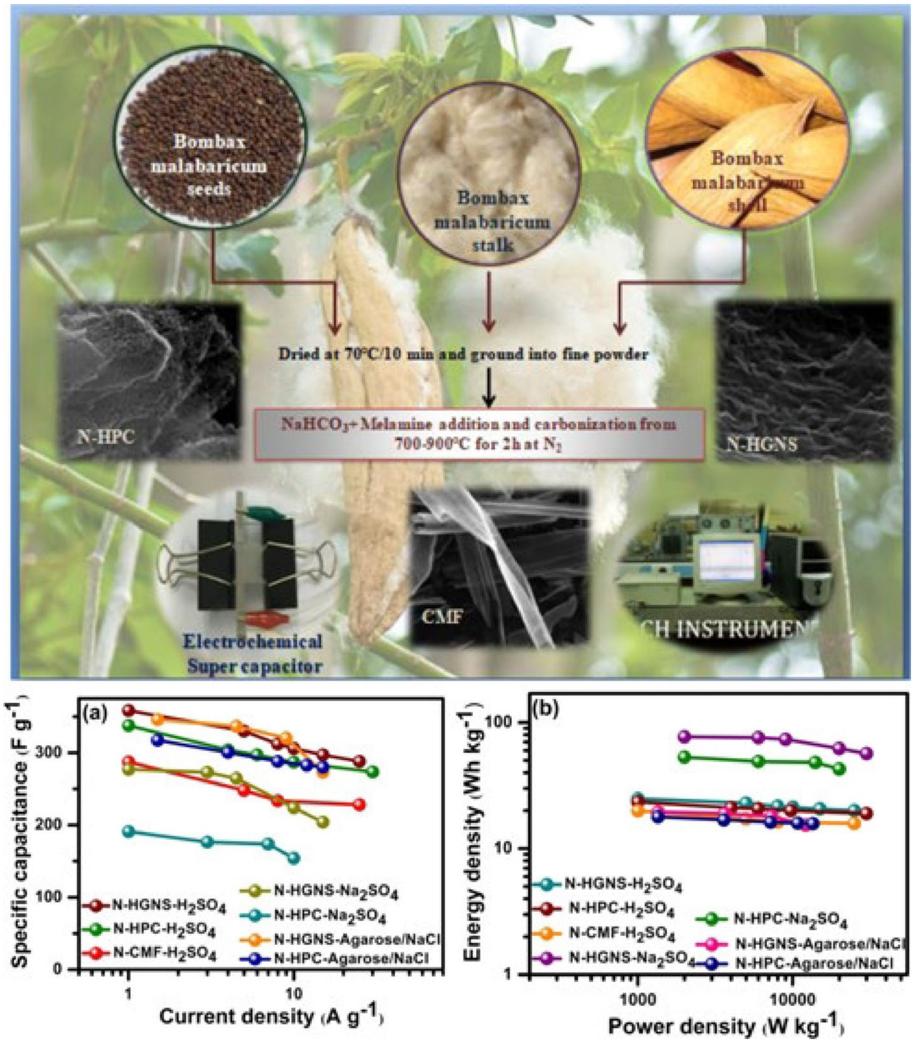

Fig. 11 The synthesis of electrodes from Bombax malabaricum biowaste and their electrochemical performance metrics in supercapacitors [76]

Besides hetero-doping, carbons that are derived from biowastes can be used in the production of composites. It is well known that metal oxides show pseudocapacitive charge storage. Making composites with carbon can enhance energy storage in supercapacitors. In a study [44], Activated carbon derived from cabbage leaves was utilized as a cost-effective, biowaste-based active electrode material. To enhance the mechanical flexibility and electrical conductivity of the electrodes, reduced graphene oxide (RGO) sheets and carbon quantum dots (CQDs) were incorporated. The study demonstrated that at an optimal AC/RGO/CQD ratio, the solid-state supercapacitor achieved maximum capacitance, along with improved scan rate performance and enhanced bending stability.

Metal oxides such as MnO_x show low electrical conductivity, strong agglomeration, and poor cycle life, which limits the use of metal oxides in high-capacity storage devices [45]. However, its electrochemical performance can be improved by producing composites using carbons derived from biowaste in a simple way, as in Fig. 11 [46].

The acidity or basicity of the porous material is closely dependent on the surface groups. If the surface contains oxygen groups, it is related to acidity and present at the basal planes' outer surface and affects chemical properties [47]. The basicity is related to the electrons that resonate at the carbon aromatic rings that attract protons, enabling the proton binding at the bare surfaces [48] (Fig. 12).

However, the development of biowaste-enhanced supercapacitors comes with its set of challenges. One notable challenge is the potential inconsistency in the quality and properties of biowaste-derived materials, which can impact the performance and reliability of these devices. Additionally, demonstrating the scalability and commercial viability of biowaste-enhanced supercapacitors is essential. Biowaste-based supercapacitors represent an innovative approach to storing electrical energy while concurrently mitigating the environmental impact of biowaste. Furthermore, incorporating biowaste into energy storage technology can play a pivotal role in diminishing the volume of biowaste disposed of in landfills, thus reducing the overall environmental footprint associated with biowaste production. In evaluating the performance of supercapacitors, it is crucial to consider the electrolyte's stability window or thermodynamic stability. A high stability window is desirable to ensure supercapacitors' safe and efficient operation. It is essential to study how the electrolyte interacts with the electroactive species within the electrode to determine the optimal electrolyte composition. In Table 1, the electrochemical performance of waste-derived ACs is given.

The structural properties of ACs have been greatly influenced by the carbon precursor, activating agent, and impregnation ratio. Ahmet et al. [49], used discarded pea skin as a precursor of AC and investigated the effect of varying impregnation ratios on the final structure. $ZnCl_2$ is used as an activating agent to be used as a catalyzer in the Scholl Condensation reaction to obtain a high carbon yield and a well-developed porous structure. Nitrogen adsorption and desorption tests were applied, and the hysteresis loops on the isotherms indicated a combination of meso and microporosity as an imgregnation ratio of AC: $ZnCl_2$ varied from 1: 1 to 1: 3. The BET results showed a high surface area with no trend in the total pore volume and average pore size. However, the yield decreased (% 28 to 21) as the impregnation ratio of $ZnCl_2$ increased. The electrochemical performance of AC was analyzed using different electrolytes, and the best specific capacitance was calculated as 192.7 Fg^{-1} in 1 M H_2SO_4, and the highest energy and power densities were measured as 17.86 $Whkg^{-1}$ and 57.33 $kWkg^{-1}$ in 1 M $LiClO_4$ electrolyte. In another work, the custard apple shell is used as a precursor, and by the same

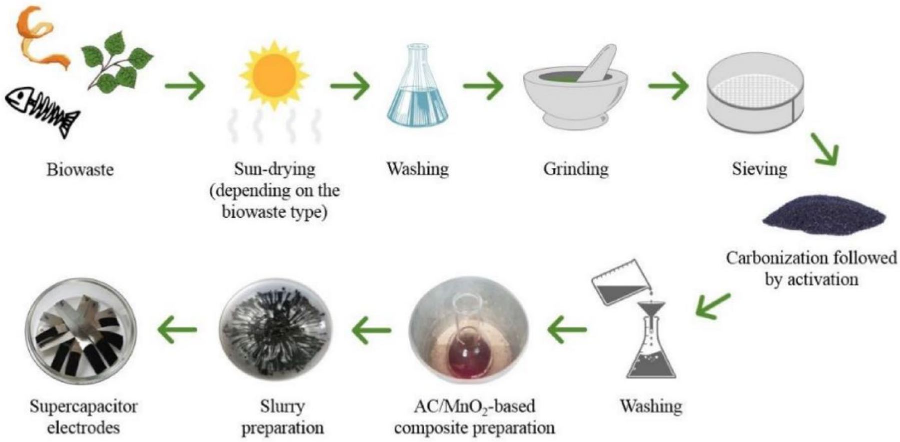

Fig. 12 A general synthesis protocol of MnO_2-AC composites [46]

Table 1 Electrochemical performance of several AC synthesized from waste materials to be used as an electrode in supercapacitors

Carbon Source	BET Surface Area ($m^2 g^{-1}$)	Total Pore Volume ($cm^3 g^{-1}$)	Specific Capacitance ($F g^{-1}$)	Power Density ($W kg^{-1}$)	Energy Density ($Wh kg^{-1}$)	Electrolyte	Capacitance Retention	Ref
Pea skin	1253.17	0.9516	192.7	1700	7.5	1 M H_2SO_4	–	[49]
Custard apple shell	1603.08	2.11	91.1	14,700	12.7	GPE	90% after 25,000 Cycles	[41]
Tea Waste	–	–	178.7	–	–	6 M KOH	99% after 10,000 Cycles	[3]
Tobacco	1296	0.52	148	51	2.66	6 M KOH	100% after 9,000 Cycles	[9]
Mung bean husks	1214	–	353	872	20.4	1 M Na_2SO_4	–	[14]
Blackfish bone	1260	–	302	–	7	6 M KOH	–	[13]
Marine Waste	1526	0.38	703	1341	0.335	SSE@DES	75% after 1,000 Cycles	[16]
Manilkara Zapota Peel	–	–	522.22	–	–	2 M KOH	95.4% after 3,000 Cycles	[17]
Wood	1364	–	224	–	–	1 M H_2SO_4	86%	[19]
Palm kernel shell	–	–	222	85.7	27.9	1 M Na_2SO_4	93% after 3,300 Cycles	[51]
Waste coffee grounds	1019	0.48	368	–	20	1 M H_2SO_4	Stable after 10,000 Cycles	[52]
Food waste	734.4	0.40	189.7	–	–	6 M KOH	–	[53]
Peanut shell	1348	–	386	1000	53.61	1 M L_2SO_4	–	[54]
Mantis shrimp shell	2465.9	–	300.3	–	–	KOH	96.7% after 10,000 Cycles	[55]
Orange peel	–	–	267	–	–	3 M KOH	89% after 5,000 Cycles	[56]
Bamboo leaf	–	–	290	–	–	1 M Na_2SO_4 and 0.5 M KOH	93% after 1,000 Cycles	[81]
Yellow mustard plant	–	–	184	7000	17.6	1 M H_2SO_4	80% after 1,500 Cycles	[57]
Canna indica	–	0.308	54.3	666.5	14.8	1 M Na_2SO_4	86% after 3,000 Cycles	[58]
Cannabis	1072	–	160	–	–	6 M KOH	101% after 3,000 Cycles	[59]
Litchi seeds	1100	0.081	320	–	–	6 M KOH	–	[60]
Wheat bran	1866.24	1.42	143.3	–	–	–	94% after 6,000 Cycles	[62]
Shrimp shell	1508	2.874	81.7	248.8	11.23	6 M NaOH	80.5% after 10,000 Cycles	[61]
YP	1631	0.78	19.9	–	–	–	–	[63]
American Ginseng	2187	–	268	10,000	18.6	6 M KOH	–	[64]
Yellow Mustard Seed	–	–	198	10,000	–	H_2SO_4	–	[57]

idea, focusing on the impregnation ratio of $ZnCl_2$, and again, the best performance is achieved by 1:3 AC: $ZnCl_2$ [41]. Brandao et al. [16] present work that synthesizes a high surface area biocarbon using marine waste by glycogen extraction from mussel cooking wastewater. The specific surface area and pore size of the biocarbon are analyzed by Brunauer-Emmet-Teller (BET), and the electrochemical properties of the biocarbon are tested via a three-electrode system in a choline chloride-based deep eutectic solvent (DES) as well as an environmentally friendly electrolyte. The surface area of the biocarbons measured 1526 $m^2 g^{-1}$, and the pore volume was 0.38 $cm^3 g^{-1}$. The specific capacitance is calculated as 657 Fg^{-1} at a current density 1 Ag^{-1} Also, the same material is tested using a two-electrode system composed of DES-based solid-state electrolyte and a specific capacitance of 703 Fg^{-1} measured at 1 Ag^{-1} current density with a 75% capacitance retention over 1000 cycles. Also, an energy density of 0.335 $Whkg^{-1}$ and a power density of 1341 Wkg^{-1} is achieved. Manikandan et al. [17] synthesized AC from Manilkara zapota peel using chemical activation with KOH as an agent and hydrothermally produced phosphorus-doped manganese dioxide (MnO_2) nanoparticles. The electrochemical tests show a specific capacitance of 522.22 Fg^{-1} at 0.5 Ag^{-1}, a cyclic stability of 95.4% after 3000 cycles. Song et al. [14], synthesized AC using mung bean husks via pyrolysis and hydrothermal routes combined with KOH activation, focusing on the effects on the porous structure. The synthesized AC showed a specific capacitance of 353 Fg^{-1} at 1 Ag^{-1}. Niu et al. [13], proposed a study focusing on synthesizing nitrogen-doped AC by pyrolysis of waste bones. Several bones, such as pork, blackfish, and eel bones, were used as carbon sources, and specific capacitance of 263, 302, and 264 Fg^{-1} were measured, respectively. Chen et al.[50], synthesized AC using tobacco waste via hydrothermal reaction followed by KOH activation, and a surface area of 112.25 $m^2 g^{-1}$ was measured using BET analysis.

A specific capacitance of 148 Fg^{-1} is measured at 0.5 Ag^{-1}, and the electrochemical tests showed that no capacitance fade was observed after 9,000 cycles. Gungor et al. [3], proposed a work focusing on the carbonization of industrial tea waste using $FeCl_3$ as a chemical activating agent. Ali et al. [51], synthesized AC from palm kernel shell by impregnating CaO from chicken eggshell waste and produced a highly porous honeycomb structure and a specific capacitance of 222 Fg^{-1} at 0.025 Ag^{-1}. Rufford et al. [52] synthesized AC from waste coffee grounds with $ZnCl_2$ treatment and used it as an electrode in supercapacitors. The electrochemical tests of the supercapacitors showed a 368 Fg^{-1} at 5 Ag^{-1}. Guo et al. [53], proposed a hydrothermal pyrolysis technique applied to food waste to produce carbon materials used as electrodes in supercapacitors. The char is produced at 220 °C and chemically activated using KOH as an agent. Also, tube furnace and microwave pyrolysis are employed to compare the resultant end products. It is seen that the char produced via microwave pyrolysis is the one that has the largest surface area amongst all, with 734.4 $m^2 g^{-1}$, and showed a specific capacitance of 189.7 Fg^{-1} at 1 Ag^{-1} with a capacitance retention of 76.96%. Le et al. [54] produced three-dimensional (3-D) porous carbon material from agricultural waste material to improve the electrochemical performance of solid-state supercapacitors. The carbon material synthesized using peanut shells has a specific surface area of 1348 m^2g^{-1}, and the electrochemical analysis using a 1 M Li_2SO_4 electrolyte showed 386 Fg^{-1} at a current density of 2 Ag^{-1}. Wei et al. [55], synthesized honeycomb-like hierarchical porous carbons from mantis shrimp shells and reached a 2465.9 $m^2 g^{-1}$ with a specific capacitance of 300.3 Fg^{-1} at a 0.05 Ag^{-1} current density. Singh et al. [56], focused on the carbonization of orange peels. They synthesized KOH-activated carbon materials, achieved a specific capacitance of 267 3 Fg^{-1} at 3 Ag^{-1} current, and showed the potential of biowaste materials in energy storage.

Kumar et al. [57], synthesized porous carbon from yellow mustard seed plant waste via a chemical activation process, and a surface area of 563 m^2g^{-1} was measured. Also, the electrochemical tests show a specific capacitance of 198 Fg^{-1} at 0.25 Ag^{-1}. Navaneethan et al. [58] synthesized AC from Canna indica via a physicochemical method. A partial lamellar structure is achieved and tested using the microwave in supercapacitors. A specific capacitance of 54.3 Fg^{-1} is measured at 0.25 Ag^{-1}. Jha et al. [59], produced high surface area AC from Cannabis using H_3PO_4 as a chemical activation agent. They showed a specific capacitance of 160 Fg^{-1} at a current density of 0.5 Ag^{-1} with a high chemical stability of 101% after 3000 cycles. Dhakal et al. [60] used litchi seeds biowastes, which normally takes more than two years to decompose in nature, and synthesized AC to use in energy storage devices, especially supercapacitors, and measured a specific capacitance of 320 Fg^{-1} at 1 Ag^{-1}. Nanda et al.[61] prepared a cost-efficient and scalable porous AC using shrimp shell waste. In the study, after grounding the shrimp waste, the shells were carbonized at 650 °C under a nitrogen atmosphere and activated using KOH. The presence of $CaCO_3$ is used as a self-template, and higher porosity is achieved. The electrochemical properties were analyzed using three different electrolytes: KOH, NaOH, and Na_2SO_4. A 225 Fg^{-1} specific capacitance is measured at 1 Ag^{-1} in 6 M NaOH electrolyte. Also, a symmetric supercapacitor cell is assembled, and a specific capacitance of 81.7 Fg^{-1} is measured. Seredych et al. [19], prepared AC from wood via oxidation, melamine, and urea treatment and carbonized at 950 °C under an inert atmosphere. The performed electrochemical tests showed that electrochemical behavior can be tuned via the existing functional groups, and they have reached 300 Fg^{-1} specific capacitances with 86% capacitance retention rate at 1 Ag^{-1} current density. Another research study [38] shows that the synthesis and performance of a defective mesoporous carbon (DMC) material for use in supercapacitors. The DMC was created using a hard templating method and boasts a high specific surface area (1350 m^2g^{-1}) and interconnected porous structure and the schematic representation was given in Fig. 13. The researchers

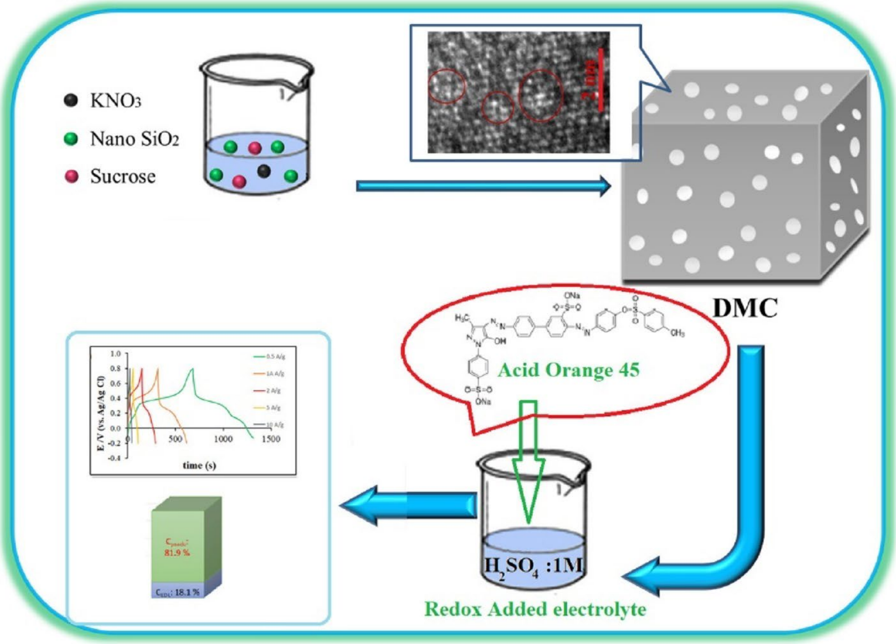

Fig. 13 DMC electrode material synthesis and uses in supercapacitor applications.
Reprinted from Defective mesoporous carbon coupled with a redox additive electrolyte for high-performance supercapacitor, Khoramjah et al. [39].

investigated the use of acid orange 45 as a redox additive in the electrolyte (H_2SO_4). The addition of this redox mediator significantly improved the supercapacitor's performance, increasing the specific capacitance to 324 Fg^{-1} and the specific energy to 11.5 $Whkg^{-1}$, a nearly threefold increase compared to using pure H_2SO_4. The improved performance is attributed to the Faradaic reactions introduced by the acid orange 45 at the electrode–electrolyte interface. The DMC electrode also demonstrated good rate capability and cycling stability. In a different study, wheat bran, straw and barley straw have been used to synthesize activated carbon and used to build supercapacitors. To analyze the electrochemical performance, GCD curves were recorded at 1 Ag^{-1}. The curves show EDLC peaks without any clear indications of redox reactions. Also, specific capacitances at different current densities are recorded in Fig. 13b to analyze the electrochemical stability [62]. To compare all these results, a commercial activated carbon coded as YP is also given in Table 1, highlighting the potential of the proposed precursors and supercapacitors [63].

Several recent studies have demonstrated the potential of biomass-derived activated carbons for high-performance supercapacitor applications. For instance, a study by [64] highlights the conversion of American ginseng waste residue into high-performance activated carbon using precarbonization and KOH activation, achieving a high specific surface area of 2187 m^2g^{-1} and specific capacitance of 268 Fg^{-1}. A symmetric supercapacitor fabricated with this carbon exhibited excellent energy (18.6 $Whkg^{-1}$) and power (10 $kWkg^{-1}$) densities, along with remarkable cycling stability (97.47% retention after 10,000 cycles). Similarly, Kumar et al. [57] reports an inexpensive carbonization process combined with chemical activation to synthesize mesoporous activated carbon from yellow mustard seed plant biowaste, achieving a high specific surface area of 563 m^2g^{-1} with both amorphous and crystalline characteristics. Sulfuric acid electrolytes were utilized to assemble symmetric supercapacitors, demonstrating excellent electrochemical performance, delivering a high specific capacitance of 198 Fg^{-1} at 0.25 Ag^{-1} and robust cyclic stability over 2100 cycles. Devi et al. [65] used walnut shell biowaste to produce AC using a hydrothermal decomposition method at 200–250 °C, aligning with green nanotechnology principles. The resulting material showed a high specific surface area of 408.8 m^2g^{-1} and delivered a specific capacitance of 204 Fg^{-1} at 1 Ag^{-1} with excellent stability over 10,000 cycles. Expanding on sustainable materials, Jafari et al. [66] explores the green synthesis of hierarchically porous carbon from biomass wastes, such as waste-activated sludge and spent coffee, achieving a high surface area of 1198 ± 60 m^2g^{-1}. Sodium acetate was used as an environmentally friendly electrolyte, supporting the development of sustainable supercapacitors. The device exhibited outstanding cycling stability, retaining 98.4% capacitance after 20,000 cycles at 10 Ag^{-1}, and achieved a maximum energy density of 15.9 $Whkg^{-1}$ at 0.2 Ag^{-1}. Additionally, using a water-based binder led to a 76% increase in capacity compared to nonaqueous binders, highlighting the eco-efficiency of the system. Whereas in [31], ACs derived from spent coffee grounds after polyphenol extraction, using hydrothermal treatment followed by physical or chemical activation. Chemically activated samples exhibited highly porous microstructures with specific surface areas up to 2330 m^2g^{-1} and delivered a capacitance of 84 Fg^{-1} at 1 Ag^{-1} in 1 M Na_2SO_4, maintaining 85% stability over 5000 cycles. In contrast, physically activated carbons showed lower porosity and less favorable morphology. The findings highlight the potential of coffee-derived secondary biowaste as a viable material for sustainable supercapacitor electrodes within a circular economy framework. Complementing these efforts, lemon peel biowaste was carbonized and chemically activated with $ZnCl_2$, producing activated carbon (ALP-600) with a high surface area of 2120 m^2g^{-1} and interconnected porosity. ALP-600 exhibited a capacitance of 180 Fg^{-1}, retained 99.7% capacity after 5000 cycles, and achieved 0.90 F in a symmetric CR2032 coin cell, further confirming the viability of biowaste as a resource for sustainable energy storage materials [67]. Despite its moderate surface area, ALP-600 demonstrated excellent electrochemical performance (152.14 Fg^{-1} in 0.5 M H_2SO_4), high energy (4.67 $Whkg^{-1}$) and power densities (8113 Wkg^{-1}), and outstanding cycling stability over 10,000 cycles with 99.5% coulombic efficiency—attributed to its hierarchical porosity and efficient ion transport. These findings collectively emphasize the viability of converting various biowastes into functional electrode materials for eco-friendly and high-performance supercapacitors [68]. Mukhiemer et al. [69], used coffee waste (CW) as a precursor for activated carbon in supercapacitor electrodes, comparing physical activation with a combined physical–chemical method using $ZnCl_2$. The physical–chemical activation significantly improved the material's properties, producing activated carbon with a higher surface area (~ 830 m^2g^{-1} vs. 458 m^2g^{-1}) and enhanced electrochemical performance. The optimized carbon showed a specific capacitance of up to 261 Fg^{-1}, an energy density of 18.3 $Whkg^{-1}$, and maintained excellent stability over 5,000 cycles. These results demonstrate the effectiveness of enhanced activation techniques in upgrading low-performing biowaste-based carbons for energy storage applications. In another study, corn stalk waste was used, dehydrated with 1 M sulfuric acid, followed by chemical activation with 5 M KOH. By optimizing the activator mass ratio (1:3) and carbonization temperature (800 °C), the resulting carbon achieved a surface area of 396.2 m^2g^{-1}, a pore volume of 0.452 cm^3g^{-1}, and a dominant microporous structure. Electrochemical tests revealed a specific capacitance of 129.08 Fg^{-1} in 3 M KOH, along with an energy density of 15.8 $Whkg^{-1}$ and power density of 2347 Wkg^{-1}—surpassing the performance of carbon produced by two-stage carbonization. This environmentally friendly dehydration method is promising for producing high-performance supercapacitor electrodes from agricultural waste [70]. Sugarcane bagasse-derived activated carbon (SBAC) as a cathode material for lithium-ion capacitors (LICs), revealing its microporous structure with a high surface area of 1906 m^2g^{-1}. When paired with lithium titanate oxide (LTO) in a CR2032 coin cell, the LIC delivered an energy density of 28.4 $Whkg^{-1}$, a power density of 1770 Wkg^{-1}, and maintained 75% capacity after 100 cycles, confirming SBAC as a promising carbonaceous cathode material for LICs [71]. Saha et al. [72] showed potential of marine biomass-derived carbon as a sustainable and high-performance electrode material for electrochemical energy storage (EES) systems. It examines the global availability and chemical composition of marine biomass, reviews key synthesis methods, and evaluates the electrochemical and mechanical properties of the resulting materials. The review also addresses the transition from research to commercialization, outlining the strategic potential of marine biomass in the energy market. Finally, it discusses current challenges and future opportunities, underscoring the importance of structural innovations and scalable production for sustainable energy solutions. In another study [73], Terminalia chebula seed stones were activatated using $ZnCl_2$ and Acs achieving up to 1382.6 m^2g^{-1} surface area with well-developed micro/mesoporous structures. The optimized electrode exhibited excellent supercapacitor performance with a specific capacitance of 328.6 Fg^{-1} at 1 Ag^{-1} and outstanding cycling stability of 98.2% over 10,000 cycles. Callistemon viminalis (Bottlebrush plant) leaves carbonized and activated with KOH at 700 °C, yielding a surface area of 925 m^2g^{-1}. The material demonstrated strong performance as a supercapacitor electrode with a specific capacitance of 283 Fg^{-1} and 97% retention, while also showing high efficiency (91.2%) in methylene blue dye removal, following Langmuir isotherm and pseudo-second-order kinetics [74]. Haj et al. [42] assembled a flexible supercapacitor using cellulose nanocrystals from brewery waste as a hydrogel electrolyte and porous carbon electrodes derived from animal bone biowaste. The device exhibits high ionic conductivity, strong mechanical durability, and excellent electrochemical performance with a specific capacitance of 804 Fg^{-1}, energy density of 18.2 $Whkg^{-1}$, and 92% retention over 6,000 cycles. An ultra-high surface area activated carbon (3600 m^2g^{-1}) was synthesized from brewer's spent grains (BSG), an abundant and low-cost brewery byproduct. This BSG-derived carbon exhibited excellent electrochemical performance, achieving a specific capacitance of 46 Fg^{-1} and strong stability in EDLCs and lithium-ion capacitors, with 85% capacitance retention after 200 h—highlighting its potential as a sustainable and high-performance material for next-generation energy storage devices [75]. An ultra-high-performance activated carbon was developed from oil shale semi-coke (OSS), a major byproduct of oil shale pyrolysis, using a microwave-assisted separation and $FeCl_3$-$ZnCl_2$ chemical activation method. The resulting material exhibited a high specific surface area (1478 m^2g^{-1}), optimized pore structure, and enhanced graphitization, delivering a specific capacitance of 185 Fg^{-1} at 1 Ag^{-1} and excellent cycling stability with 99.5% capacitance retention after 5000 cycles—offering a promising and sustainable approach for converting industrial waste into low-cost, high-efficiency supercapacitor electrode materials [76]. In [77], fallen teak leaves were used in a simple, low-cost, and eco-friendly method involving integrated pyrolysis and activation. The resulting monolithic carbon achieved a high surface area of 489.81 m^2g^{-1}. It demonstrated excellent supercapacitor performance with a specific capacitance of 280 Fg^{-1} in 1 M H_2SO_4, highlighting its potential as a sustainable electrode material for energy storage and effective biomass waste valorization.Kusha grass (*Desmostachya bipinnata*), a widely available biowaste, was used to synthesize highly capacitive activated carbon (DP-AC) through a chemical process followed by KOH activation. The resulting few-layered carbon exhibited excellent electrochemical performance, including a specific capacitance of 218 Fg^{-1}, an energy density of 19.3 $Whkg^{-1}$, a power density of 277.92 Wkg^{-1}, and outstanding cycling stability over 5000 cycles—making it a promising and sustainable electrode material for supercapacitor applications. Purple corncob, an abundant agricultural biowaste, was used to synthesize activated carbon via KOH activation followed by thermal treatment at 700 °C under inert atmosphere, yielding a promising electrode material for supercapacitors. The optimized sample, activated with 10% KOH, exhibited a surface area of 728 m^2g^{-1} and delivered high specific capacitances of 195 Fg^{-1} in 1 M H_2SO_4 and 116 Fg^{-1} in 1 M KOH at 0.5 A/g, along with 76% capacitance retention after 50,000 cycles—demonstrating the potential of purple corncob-derived carbon for efficient and durable energy storage applications [78]. Bio-waste-derived activated porous carbon was synthesized through a high-temperature KOH activation process under an inert atmosphere, aiming to develop cost-effective and sustainable energy storage materials. The resulting carbon exhibited a high specific surface area of 811.8 m^2g^{-1}, a mean pore size of 1.81 nm, and an impressive

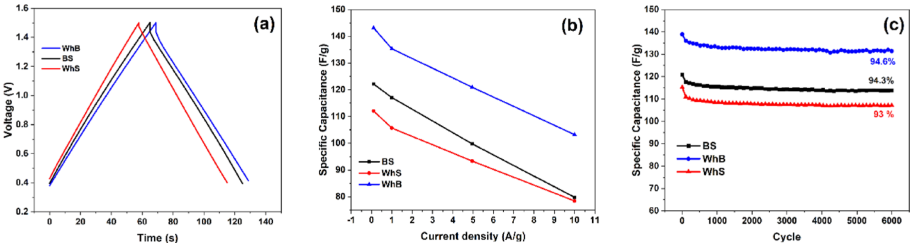

Fig. 14 The electrochemical results gathered from activated carbon synthesized from wheat waste. Reprinted from The Impact of Biowaste Composition and Activated Carbon Structure on the Electrochemical Performance of Supercapacitors, Abdisattar et al. [47].

specific capacitance of 565.2 Fg^{-1}, with 98% capacitance retention over 10,000 cycles. A solid-state symmetric supercapacitor assembled from this material delivered a high energy density of 24.5 $Whkg^{-1}$ at a power density of 801.82 Wkg^{-1} with 96% capacity retention. These results demonstrate the material's strong potential for high-performance, eco-friendly energy storage applications [79]. Quercus infectoria (Qui) biomass was used for the first time to produce activated carbon via carbonization and acid–base activation, with KOH activation yielding the most effective supercapacitor electrodes. The KOH-activated carbon (Qui-KOH) demonstrated a threefold increase in capacitance, achieving 89 Fg^{-1} at 1 Ag^{-1}. It also delivered a maximum energy density of 8.46 $Whkg^{-1}$ at a power density of 407.64 W/kg, outperforming other electrodes. These results confirm Qui-KOH as a low-cost, eco-friendly, and efficient material for high-performance energy storage applications [80] (Fig. 14).

Porous activated carbon electrodes were successfully synthesized from a blend of cassava tubers and bamboo stems using 4 M KOH chemical activation, yielding a micro-mesoporous structure ideal for enhanced electrolyte ion storage. The resulting electrode EDLC behavior with a specific capacitance of 43.44 Fg^{-1}, energy density of 4.81 $Whkg^{-1}$, and power density of 178.64 Wkg^{-1}, highlighting its potential as a sustainable and effective material for energy storage applications. Jayachandran et al. [81], synthesized AC from bamboo leaves using a carbonization process followed by chemical activation using KOH. The effect of using different electrolytes on the specific capacitance is analyzed, and it is observed that using a mixed electrolyte composed of 1 M Na_2SO_4 and 0.5 M KOH, a maximum specific capacitance of 290 Fg^{-1} is measured at 1 Ag^{-1} current density. Also, the capacity retention is measured as 93% after 1000 cycles at 10 Ag^{-1} and presents the potential of using mixed electrolytes in supercapacitors. A 3D porous activated carbon monolith was synthesized from bamboo stem through a two-step carbonization and chemical activation process, enhancing its suitability as a supercapacitor electrode. The optimized sample demonstrated excellent electrochemical performance, with a specific capacitance of 168.8 Fg^{-1}, an energy density of 23.44 $Whkg^{-1}$, and a power density of 84.46 Wkg^{-1}—attributes strongly influenced by its hierarchical 3D structure and well-developed porosity [82]. Nitrogen-doped activated carbon (N-ACC) derived from *Coprinus comatus* was synthesized via chemical activation and nitrogen doping, resulting in a material with a high surface area (976.96 m^2g^{-1}), elevated nitrogen content (11.53 wt. %), and excellent hydrophilicity. As a supercapacitor electrode, N-ACC exhibited outstanding electrochemical performance, including a specific capacitance of 346 Fg^{-1} at 1 Ag^{-1}, 75% retention at 10 Ag^{-1}, and in a symmetric configuration, delivered an energy density of 14.63 $Whkg^{-1}$ at 810 Wkg^{-1} with 92% capacitance retention after 10,000 cycles—demonstrating its strong potential for high-performance energy storage applications. Palm frond waste was used to successfully produce porous activated carbon through a sustainable process combining pyrolysis at 600 °C in nitrogen and physical activation at 800 °C with steam. The resulting material exhibited a high carbon purity (up to 80%), a specific surface area of 356 m^2g^{-1}, rich surface nanopores, and good amorphous structure, achieving a specific capacitance of 86 Fg^{-1}—demonstrating strong potential for use in energy storage devices, air and water purification systems, and other eco-friendly applications. Hayashi et al. [83], proposed an innovative method for fabricating graphene aerogels (GAs) with tailored architectures through the laser upcycling of hemoglobin, a protein-based biowaste. Laser scanning enables the simultaneous induction of localized graphitization and structural patterning along the scanning path, allowing for the direct fabrication of engineered graphene aerogels (GAs). These aerogels are enriched with fibrous graphitic structures, which significantly increase their surface area. This enhancement is largely attributed to the presence of iron in hemoglobin, which facilitates the formation of iron-based nanoparticles that act as catalysts for the growth of nanostructured graphene. Due to their high conductivity and distinctive morphology, these laser-derived GAs serve effectively as electrodes in 3D symmetrical supercapacitors, delivering a high specific capacitance (~54.9 F g^{-1}) and excellent cycling stability. This highlights the potential of laser upcycling as a sustainable approach for developing high-performance energy storage materials.

In parallel, carbon nanoparticles derived from cooking oven biowaste (WCP) are integrated into polyaniline (PANI) through in-situ chemical oxidative polymerization to enhance their electrochemical properties for supercapacitor use. The resulting WCP-PANI composite electrodes exhibit superior charge storage performance, benefiting from the synergistic effect of electric double-layer capacitance provided by WCP and the pseudocapacitance from PANI. Increasing the WCP content raises the work function of PANI, leading to improved charge-trapping efficiency and stable areal capacitance even at high scan rates and current densities—indicating strong rate capability and reduced diffusion resistance. Additionally, extended polymerization time strengthens the interaction between PANI and WCP, further enhancing charge transfer, leading to over 600-fold capacitance improvement compared to pure PANI, and a remarkable 550% increase in power density with only a 1% reduction in energy density. This rational design underscores the potential of WCP-PANI composites as high-performance, sustainable electrode materials for next-generation green supercapacitors [84]. Ma et al. [85], used sunflower heads, which is a readily available agricultural biowaste, for the first time as a renewable precursor to synthesize porous carbon (PC) for supercapacitor electrodes. The carbon was prepared through a simple and cost-effective carbonization process followed by KOH activation, yielding a material with a hierarchical pore structure, high surface area (1032 m^2g^{-1}), and significant oxygen content (21 wt %). These features contributed to excellent electrochemical performance, with the sunflower head-derived carbon (SFHCs) achieving a specific capacitance of 345 Fg^{-1} at 1 Ag^{-1} in 6 M KOH and retaining 81% capacitance at 20 Ag^{-1}. Furthermore, the SFHC-based symmetric supercapacitor delivered a high energy density of 9.2 $Whkg^{-1}$ at a power output of 482 Wkg^{-1}, highlighting the promise of this biowaste-derived carbon for sustainable, high-performance energy storage devices. De Souza et al. [86], fabricated high-performance supercapacitor electrodes using acai seed biowaste as a carbon precursor. Porous carbon materials were produced via carbonization followed by KOH activation, generating a hierarchical pore structure with tunable micro- and mesoporosity. The resulting carbons exhibited high specific surface areas and total pore volumes, contributing to excellent electrochemical performance with a specific capacitance of 346 Fg^{-1} at 1 $mAcm^{-2}$ and 88% capacitance retention after 5000 cycles at 7 $mAcm^{-2}$ in 1 M KOH. These findings position acai seed-derived carbons among the top-performing biomass-based materials for supercapacitors, offering a sustainable solution for large-scale biowaste valorization. Wen et al. [87], a cost-effective and straightforward strategy to produce high-performance porous carbon materials from peanut shell biowaste through $CoCl_2$-catalyzed graphitization combined with $ZnCl_2$ activation. The resulting carbons feature a high specific surface area (1745–2257 m^2g^{-1}), natural nitrogen and oxygen co-doping, and a hierarchical porous architecture. These properties collectively enable outstanding supercapacitor performance, including a high specific capacitance of 343 Fg^{-1} at 0.5 Ag^{-1}, excellent cycling stability with 90.9% retention after 10,000 cycles at 10 Ag^{-1} in 6 M KOH, and an energy density of 42 $Whkg^{-1}$ at 375 Wkg^{-1} in an organic electrolyte. This approach effectively balances conductivity and surface area, offering a promising route for sustainable energy storage materials derived from biomass. Another study [88], addresses the environmental challenge of banana trunk biowaste by proposing a novel and scalable method to convert it into uniform carbon fibers for energy storage applications. These carbon fibers were further functionalized with nanoparticles of Au, Ag, CeO_2, $CoFe_2O_4$, and Au/Fe_2O_4 to enhance their electrochemical properties. CV analysis revealed that fibers coated with Ag and Au exhibited significantly improved redox behavior and higher response currents than unmodified fibers. The enhanced performance is attributed to the high oxygen functionality of the carbon matrix and the synergistic interaction with the metal nanoparticles, highlighting the potential of this approach for sustainable electrode material development. Chinese bitter melon (CBM) biowaste used as a carbon networka and simultaneously incorporated with lanthanum oxide (La_2O_2) and tin oxide (SnO_2) to form La/Sn-HPCs. The resulting 3D porous framework, enriched with N/O functional groups and pseudo-capacitive La/Sn centers, delivers a high specific capacitance of 623 $F\,g^{-1}$ at 1 $A\,g^{-1}$ in 0.5 M Na_2SO_4. In the presence of VO^{2+} redox additives, capacitance significantly increases to 1557 $F\,g^{-1}$ with strong rate capability (65.1% retention at 30 $A\,g^{-1}$). The symmetric La/Sn-HPCs supercapacitor achieves a peak energy density of 97.6 $Wh\,kg^{-1}$ at 900 $W\,kg^{-1}$ and maintains 79.6% capacitance after 14,000 cycles. DFT analysis confirms strong La/Sn–carbon bonding and enhanced charge redistribution, while VO^{2+} additives further boost electron transport and ionic conductivity, highlighting the promise of pseudo-active HPCs from biomass for advanced energy storage systems [89]. In another study [90], Kochia, a traditional Chinese herbal medicine, is often discarded as biowaste after extraction. However, its high lignocellulose content and tubular structure make it a promising precursor for carbon materials. After pyrolysis at 800 °C and activation at a 1:5 carbon-to-base ratio, a hierarchical porous carbon (KAC-5) with a high surface area of 1441.30 $m^2\,g^{-1}$ is obtained. KAC-5 shows excellent electrochemical performance, with a specific capacitance of 284 $F\,g^{-1}$ at 1 $A\,g^{-1}$ and 90.31% retention after 10,000 cycles in 6 M KOH. A symmetric supercapacitor based on KAC-5 achieves an energy density of 12.3 $Wh\,kg^{-1}$ and retains 88.83% capacitance over 10,000 cycles, demonstrating its potential as a sustainable electrode material. Kenaf fibers were carbonized and chemically activated with KOH. The resulting AC-800 sample was tested in a supercapacitor and exhibited the highest specific capacitance of 100 F g^{1} in 6 M KOH electrolyte and showed the potential of a low-cost, lightweight, and sustainable electrode material for supercapacitor applications [91]. A sustainable electrode design for symmetrical supercapacitors using carbon derived from peanut shells is presented in [92]. Freestanding polymer/carbon nanofiber electrodes were fabricated by solution blowing polyvinylidene fluoride (PVDF) with ultra-high carbon content. The electrodes achieved excellent electrochemical performance, with areal capacitance up to 1120 mF cm^{-2} in aqueous electrolytes and retained 91% and 96.4% of their initial capacitance after 10,000 cycles in aqueous and organic electrolytes, respectively. The high conductivity and surface area of the biowaste-derived fibrous architecture make it a promising candidate for advanced energy storage systems. Cow urine, an animal biowaste, was utilized as a sustainable precursor for the synthesis of carbon-based electrode materials for supercapacitors. Porous, heteroatom-doped carbon materials were prepared through direct pyrolysis at 700 °C (CCUR-700) and further enhanced via KOH activation (A-CCUR-700). The A-CCUR-700 sample exhibited a high specific surface area (2651.7 m^{2}g^{-1}), rich nitrogen and sulfur doping, and improved electrochemical properties. A specific capacitance of 165 Fg^{-1} at 0.5 Ag^{-1} was achieved, and a symmetric supercapacitor device assembled with A-CCUR-700 delivered an energy density of 22.9 Whkg^{-1} and a power density of 5100 Wkg^{-1}, with 95.3% capacitance retention after 5000 cycles. These findings demonstrate that cow urine can be effectively converted into low-cost, high-performance carbon materials for sustainable energy storage applications [93]. In study [94], AC produced from sunflower shell biowaste using KOH activation. The influence of activation temperature and KOH-to-precursor mass ratio on electrochemical performance was systematically investigated. The optimized sample, HPCS-800–2, prepared at 800 °C for 2 h, exhibited well-defined graphitic layers (~ 0.34 nm spacing) and a reduced ID/IG ratio (0.797), indicating improved graphitization compared to non-activated carbon (0.917). A high specific capacitance of 403 Fg^{-1} at 0.5 Ag^{-1} was achieved. Furthermore, a symmetric HPCS-800–2//HPCS-800–2 supercapacitor delivered an energy density of 20.84 Whkg^{-1}, outperforming the commercial YP50-based device (8.18 Whkg^{-1}), highlighting its potential for advanced energy storage applications. In study [95], activated carbon (AC) was derived from inexpensive black seed fennel flower (LcFF) using a chemical activation technique. Among the resulting materials, the activated fennel flower (Ac-FF) exhibited consistent electrochemical performance, which was further enhanced by integrating it with functionalized graphene oxide (FGO). A ternary nanocomposite (POAP/FGO/Ac-FF) was then developed by depositing a thin layer of polyorthoaminophenol (POAP) onto the FGO/Ac-FF structure. SEM and TEM analyses showed a layered morphology that supported improved ion diffusion. The composite featured a high specific surface area of 2199.2 m^{2}g^{-1} and delivered a specific capacitance of 1400.2 Fg^{-1} at a current density of 2 Ag^{-1} in a three-electrode setup. Furthermore, it retained 94.4% of its capacitance after 5000 cycles, demonstrating excellent cycling stability. These findings highlight the effectiveness of biowaste-derived nanocomposites for high-performance supercapacitor applications. In study [96], porous carbon nanosheets were synthesized from pineapple peel biowaste at various activation temperatures (PP-600, PP-700, PP-800). The PP-800 sample exhibited a high specific surface area and hierarchical pore structure, making it suitable for supercapacitor applications. A solid-state symmetric supercapacitor assembled with PP-800 electrodes and PVA gel electrolyte delivered an energy density of ~ 43 Whkg^{-1} at a power density of ~ 1 kWkg^{-1}, with 83% capacitance retention after 10,000 cycles. These findings highlight the potential of pineapple peel-derived carbon as a high-performance electrode material for energy storage devices.

3.6 Challenges and limitations

Cycle life is one of supercapacitors' most critical features, which sets them apart from batteries. Batteries typically exhibit poor cycle life, with lifespans often limited to hundreds or a maximum of a few thousand cycles. In contrast, supercapacitors demonstrate exceptional cycle life with very high charge retention. However, it's essential to note that when incorporating carbon derived from biowaste with materials such as metal–organic frameworks, hybrid nanocomposites, metal sulfides, or metal phosphides, there can be a reduction in charge retention rates. This reduction occurs due to redox reactions that may change the volume of the supercapacitors and modify the electrode composition, leading to a change in performance. Nevertheless, it's worth emphasizing that this reduced charge retention in supercapacitors is still significantly better than typically observed in batteries [29, 97]. Moreover, the compositions of such biowaste materials from available sources, including agricultural residues, food processing by-products, and organic municipal waste, span a broad spectrum. This certainly has implications for the type of biowaste, conditions under which it was produced, and processes involved in its conversion into electrode material, all connected with the diversity in its chemical and physical properties. In most cases, this variability leads to quite a significant inconsistency in the electrodes' properties from biowaste. These inconsistencies may bring about variations in conductivity, surface area, and electrochemical stability, parameters that are of the essence regarding the performance of supercapacitor electrodes. One of the primary challenges associated with biowaste-derived electrodes is the presence of impurities. Biowaste materials frequently contain a variety of contaminants, such as heavy metals, inorganic salts, and organic compounds, that can interfere with the performance of the electrodes. These impurities can block active sites, reduce conductivity, and cause degradation of the electrode material, thereby negatively impacting the overall efficiency and lifespan of supercapacitors. Several methods can be employed to remove or mitigate these impurities, including washing with deionized water or acid solutions to remove inorganic salts and heavy metals and thermal pre-treatment to volatilize certain organic contaminants [50, 98]. More advanced techniques, such as chemical extraction or adsorption methods, may be necessary for more persistent impurities. The choice of purification method depends on the specific type of biowaste and the nature of the impurities present. The effectiveness of the purification process should be carefully evaluated to ensure that the resulting activated carbon is of sufficient quality for supercapacitor applications [99, 100]. Another tremendous challenge is the absence of standard order and specification for biowaste-derived material. While traditional material standards and protocols are very well established, there is an evident lack of uniformity regarding standard procedures and specifications for producing, characterizing, and evaluating the performance of biowaste-derived electrodes. This lack of standardization is bound to result in variability in the research findings and poor comparability of results from various studies. The same also makes it tough for manufacturers to assure the quality and reliability of their products, thus severely hampering diffuse adoption and integration into commercial products. Compared to traditional electrode materials, research relating to biowaste-derived electrodes is still in the infant stage. Much more detailed and systematic studies are needed to understand the properties of these materials and optimize their performance, as promising developments have been reported. The research efforts must include identifying the most appropriate biowaste types for producing electrodes, developing efficient and scalable processing methods, and finding solutions for impurity and variability problems. Moreover, long-term studies need to be performed to check the durability and stability of biowaste-derived electrodes under real-world operating conditions. In a nutshell, even though biowaste-derived electrodes have great potential for creating sustainable solutions in energy storage applications, several pertinent problems remain to be attended to before such enormous potential is tapped. This encompasses the management of variability and impurities of biowaste materials, developing effective and scalable production processes, ensuring uniform quality and performance, creating standardized procedures, and undertaking detailed research to optimize their properties. In light of the challenges discussed above, it will thus involve a combined effort on the part of researchers, industry stakeholders, and policymakers to develop innovative solutions and create an enabling environment for the uptake of electrodes derived from biowaste. Biowaste materials, which originate from various sources such as agricultural residues, food processing by-products, and organic municipal waste, exhibit a broad spectrum of compositions. This diversity in their chemical and physical properties is influenced by factors such as the type of biowaste, the conditions under which it was generated, and the specific processing methods employed to convert it into electrode material. Such variability often results in significant inconsistencies in the properties of the electrodes derived from biowaste. These inconsistencies can manifest in several ways, including variations in conductivity, surface area, and electrochemical stability, all of which are critical for the performance of supercapacitor electrodes. One of the primary challenges associated with biowaste-derived electrodes is the presence of impurities. Biowaste materials frequently contain a variety of contaminants, such as heavy metals, inorganic salts, and organic compounds, that can interfere with the performance of the electrodes. These impurities can block the active sites, reduce conductivity, and cause degradation of the electrode material, thereby negatively impacting the overall efficiency and lifespan of supercapacitors. Removing or mitigating these impurities often requires additional processing steps, which can further complicate the production process. Biowaste conversion into usable electrode materials is a complex and multi-step process. It typically involves several stages: collection, pre-treatment (such as drying and grinding), chemical or thermal treatment (such as pyrolysis or hydrothermal carbonization), activation, and finally, fabrication into electrode form. Each of these stages can introduce additional variability and potential points of failure. Moreover, these processes can be time-consuming and costly, requiring significant energy input and expensive chemicals or specialized equipment. This complexity poses a substantial barrier to the large-scale production of biowaste-derived electrodes. Scaling up the production to meet industrial demands introduces further challenges. Maintaining consistent quality and performance across large batches is difficult, as small deviations in the processing conditions can lead to significant differences in the final product. Additionally, the infrastructure required for large-scale production is substantial, involving the equipment for processing the biowaste and systems for quality control, waste management, and logistics. Given the high initial investment and operational costs, the economic feasibility of such large-scale production is often questionable. Another significant hurdle is the lack of standardized procedures and specifications for biowaste-derived materials. Unlike traditional materials with well-established standards and protocols, biowaste-derived electrodes lack uniform guidelines for their production, characterization, and performance evaluation. This lack of standardization can lead to inconsistencies in research outcomes and hinder comparing results from different studies. It also makes it difficult for manufacturers to ensure the quality and reliability of their products, thereby impeding the widespread adoption and integration of biowaste-derived electrodes into commercial products. Compared to traditional electrode materials, research on biowaste-derived electrodes is still in its infancy. While promising developments have been made, much more extensive and systematic studies are needed to fully understand their properties and optimize their performance. Research efforts must focus on identifying the most suitable types of biowaste for electrode production, developing efficient and scalable processing methods, and addressing the issues related to impurities and variability. Furthermore, long-term studies are necessary to evaluate the durability and stability of biowaste-derived electrodes under real-world operating conditions. In conclusion, while biowaste-derived electrodes hold great promise for sustainable energy storage solutions, several significant challenges must be addressed to realize their full potential. These include managing the variability and impurities of biowaste materials, developing efficient and scalable production processes, ensuring consistent quality and performance, establishing standardized procedures, and conducting extensive research to optimize their properties. Addressing these challenges will require coordinated efforts from researchers, industry stakeholders, and policymakers to develop innovative solutions and create a supportive environment for adopting biowaste-derived electrodes.

Biowaste materials, which originate from various sources such as agricultural residues, food processing by-products, and organic municipal waste, exhibit a broad spectrum of compositions. This diversity in their chemical and physical properties is influenced by factors such as the type of biowaste, the conditions under which it was generated, and the specific processing methods employed to convert it into electrode material. Such variability often results in significant inconsistencies in the properties of the electrodes derived from biowaste. These inconsistencies can manifest in several ways, including variations in conductivity, surface area, and electrochemical stability, all of which are critical for the performance of supercapacitor electrodes. One of the primary challenges associated with biowaste-derived electrodes is the presence of impurities. Biowaste materials frequently contain a variety of contaminants such as heavy metals (e.g., lead, cadmium, mercury), inorganic salts (e.g., sulfates, phosphates, chlorides), and organic compounds (e.g., pesticides, herbicides, toxins) that can interfere with the performance of the electrodes. These impurities can block the active sites, reduce conductivity, and cause degradation of the electrode material, thereby negatively impacting the overall efficiency and lifespan of supercapacitors. Removing or mitigating these impurities often requires additional processing steps, such as washing with acids or chelating agents, which can further complicate and increase the cost of the production process. For example, biowaste derived from industrial processes may contain heavy metals, while agricultural waste might have pesticide residues. These contaminants necessitate specific pre-treatment steps tailored to the type of biowaste, adding complexity to the manufacturing process. Furthermore, the inherent variability in biowaste composition makes it challenging to achieve consistent electrode properties. Even within the same type of biowaste, variations in factors like the source material's age, storage conditions, and geographical location can lead to significant differences in the final electrode characteristics. This variability necessitates stringent quality control measures throughout production, adding to the overall cost and complexity. Scaling up the production of biowaste-derived electrodes to meet industrial demands presents significant logistical and economic hurdles. The infrastructure required for large-scale processing, including collection, pre-treatment, carbonization, activation, and electrode fabrication, is substantial. Ensuring a consistent supply of biowaste with uniform quality and composition is also a major challenge. Moreover, the cost-effectiveness of large-scale production needs careful evaluation, considering factors such as transportation, storage, and pre-treatment of the biowaste, as well as the energy consumption and capital costs associated with the various processing steps. In conclusion, while biowaste-derived electrodes are promising for sustainable energy storage solutions, several significant challenges must be addressed to realize their full potential.

3.7 Economic and environmental considerations

A detailed economic analysis comparing the production costs of biowaste-derived materials with established methods for supercapacitor electrodes is crucial for evaluating the commercial viability of this approach. Factors influencing production costs include the cost of biowaste acquisition (which can range from very low for readily available waste streams to moderate for purpose-grown biomass), pre-treatment steps, carbonization and activation processes, and electrode fabrication. While biowaste is often inexpensive or even free, the overall cost-effectiveness depends heavily on the efficiency and scalability of the conversion processes. For example, while effective, chemical activation methods can involve using relatively expensive activating agents like KOH. Furthermore, the energy consumption associated with pyrolysis and other thermal treatments can contribute significantly to the overall cost. Direct comparison with other methods, such as synthesizing activated carbon from petroleum coke or producing graphene-based electrodes, requires careful consideration of all these factors. Such a detailed cost analysis is an important area for future research.

From an environmental perspective, utilizing biowaste for supercapacitor electrodes offers several potential benefits. It reduces reliance on fossil fuel-derived materials, minimizes waste disposal issues, and can contribute to a circular economy. However, it's essential to assess the overall environmental impact of the entire production chain. Factors to consider include the energy consumption and greenhouse gas emissions associated with various processing steps, the use and disposal of chemical activating agents, and the potential for water pollution. A comprehensive life-cycle assessment (LCA) is necessary to quantify these environmental impacts and compare them with those of alternative electrode materials. While a full LCA is beyond the scope of this mini-review, it is a crucial area for future investigation to ensure the genuine environmental sustainability of biowaste-derived supercapacitor electrodes.

4 Conclusion

Supercapacitor electrodes derived from biowaste represent an emerging technology with the potential to offer both environmental sustainability and cost-effectiveness. These electrodes can be crafted from various biowaste materials, including plant fibers, food waste, and agricultural residues. This paper reviews multiple activated carbon samples sourced from biowaste and categorizes them into distinct preparation methods. Nevertheless, integrating biowaste as an electrode material in graphite or activated carbon adds previously hidden value to the economy. This endeavor presents a challenge, but its benefits lie in harnessing readily available resources and expanding skillsets and knowledge. It demonstrates an interdisciplinary trajectory, transforming biowaste from various plant waste sources into electrode materials for energy storage devices. This paradigm shift illustrates how the energy-harvesting economy can evolve by reutilizing biowaste.

Additionally, the increased public awareness surrounding organic waste has fueled demand, further highlighting the potential for implementing biowaste as a resource for electrode materials. Building a sustainable community dedicated to well-structured and detailed case studies from institutes, industry stakeholders, and enthusiastic individuals through practice and communication will boost this movement. The progress in biowaste classification, sourcing, segregation, and treatment will need to be emphasized, as it sets new standards for the quality of future products in emerging markets. Ultimately, these factors make biowaste-based supercapacitor electrodes an appealing alternative to traditional counterparts, offering the potential to contribute to developing more sustainable and environmentally friendly energy storage systems.

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Author contributions

I. D. Yildirim contributed to the writing of the original draft and editing. B. Bakhtiari contributed to the writing of the review. A. Gungor and E. Erdem contributed to writing the original draft, review, and editing.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethical approval and consent to participate

Not applicable.

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Competing interests

The authors declare no competing interests.

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References

1. Mensah-Darkwa K, et al. Supercapacitor energy storage device using biowastes: a sustainable approach to green energy. Sustainability. 2019;11(2):414.
2. Simon P, Gogotsi Y. Materials for electrochemical capacitors. Nat Mater. 2008;7(11):845–54.
3. Güngör A, et al. Chemically exfoliated refined carbon from industrial tea waste for capacitive energy storage. Phys Scr. 2024. https://doi.org/10.1088/1402-4896/ad29dc.
4. Omidvar M, et al. Fabrication of an efficient supercapacitor based on defective mesoporous carbon as electrode material utilizing reactive blue 15 as novel redox mediator for natural aqueous electrolyte. Fuel. 2023;347:128472.

5. Shahmohammadi A, Dalvand S, Baheri H. Electrochemical synthesis of hybrid nanostructure of nickel cobalt phosphide/molybdenum disulfide on nickel foam as an effective electrode material in supercapacitor. Mater Chem Phys. 2024;317:129150.
6. Panja T, Bhattacharjya D, Yu J-S. Nitrogen and phosphorus co-doped cubic ordered mesoporous carbon as a supercapacitor electrode material with extraordinary cyclic stability. J Mater Chem A. 2015;3(35):18001–9.
7. Gogotsi Y, Presser V. Carbon nanomaterials. Boca Raton: CRC Press; 2006.
8. Asghari A, et al. Reactive red 198 as high-performance redox electrolyte additive for defective mesoporous carbon-based supercapacitor. Int J Hydrogen Energy. 2023;48(26):9776–84.
9. Chen H, et al. An activated carbon derived from tobacco waste for use as a supercapacitor electrode material. New Carbon Mater. 2017;32(6):592–9.
10. Dalvand S, et al. A review on carbon material-metal oxide-conducting polymer and ionic liquid as electrode materials for energy storage in supercapacitors. Ionics. 2024;30(4):1857–70.
11. Kayode SE, González FJ. Treatment of biowaste for electrodes in energy storage applications: a brief review. J Compos Sci. 2023;7(3):127.
12. Sadat Z, et al. Fabrication of a novel porous nanostructure based on $NiCuFe_2O_4$@ MCM-48, embedded with graphene oxide/poly (p-phenylenediamine) to construct an efficient supercapacitor. Sci Rep. 2024;14(1):3137.
13. Niu L, et al. Waste bones derived nitrogen–doped carbon with high micropore ratio towards supercapacitor applications. J Colloid Interface Sci. 2019;547:92–101.
14. Song M, et al. Biowaste-based porous carbon for supercapacitor: the influence of preparation processes on structure and performance. J Colloid Interface Sci. 2019;535:276–86.
15. Sundriyal S, et al. Advances in bio-waste derived activated carbon for supercapacitors: trends, challenges and prospective. Resour Conserv Recycling. 2021;169:105548.
16. Brandão AT, et al. Renewable carbon materials as electrodes for high-performance supercapacitors: from marine biowaste to high specific surface area porous biocarbons. ACS Omega. 2023. https://doi.org/10.1021/acsomega.3c00816.
17. Manikandan S, et al. Bifunctional activities of phosphorus doped MnO_2 with activated carbon from Manilkara zapota peel bio-waste for supercapacitor and photocatalytic degradation of organic dye. Ionics. 2023;29(2):769–92.
18. Frackowiak E, Beguin F. Carbon materials for the electrochemical storage of energy in capacitors. Carbon. 2001;39(6):937–50.
19. Seredych M, et al. Surface functional groups of carbons and the effects of their chemical character, density and accessibility to ions on electrochemical performance. Carbon. 2008;46(11):1475–88.
20. Utetiwabo W, et al. Electrode materials derived from plastic wastes and other industrial wastes for supercapacitors. Chin Chem Lett. 2020;31(6):1474–89.
21. Dzikunu P, et al. Waste-to-carbon-based supercapacitors for renewable energy storage: progress and future perspectives. Mater Renew Sustain Energy. 2025;14(1):1–45.
22. Najib S, Erdem E. Current progress achieved in novel materials for supercapacitor electrodes: mini review. Nanoscale Adv. 2019;1(8):2817–27.
23. Krishnan SG, et al. Pore size matters!—a critical review on the supercapacitive charge storage enhancement of biocarbonaceous materials. Crit Rev Solid State Mater Sci. 2023;48(1):1–56.
24. Lee J, Kim J, Hyeon T. Recent progress in the synthesis of porous carbon materials. Adv Mater. 2006;18(16):2073–94.
25. Kim C, et al. Influence of pore structure and cell voltage of activated carbon cloth as a versatile electrode material for capacitive deionization. Carbon. 2017;122:329–35.
26. Davies A, Yu A. Material advancements in supercapacitors: from activated carbon to carbon nanotube and graphene. Can J Chem Eng. 2011;89(6):1342–57.
27. Faraji S, Ani FN. The development supercapacitor from activated carbon by electroless plating—a review. Renew Sustain Energy Rev. 2015;42:823–34.
28. Yildirim ID, et al. Strategies to reach ultrahigh capacitance values for supercapacitors: materials design. Turk J Phys. 2021;45(4):178–84.
29. Huang C, et al. Boosting the energy density of supercapacitors by designing both hollow NiO nanoparticles/nitrogen-doped carbon cathode and nitrogen-doped carbon anode from the same precursor. Chem Eng J. 2022;431:134083.
30. Reza MS, et al. Preparation of activated carbon from biomass and its' applications in water and gas purification, a review. Arab J Basic Appl Sci. 2020;27(1):208–38.
31. Adan-Mas A, et al. Coffee-derived activated carbon from second biowaste for supercapacitor applications. Waste Manag. 2021;120:280–9.
32. Kandasamy SK, et al. Paradisiaca/Solanum tuberosum biowaste composited with graphene oxide for flexible supercapacitor. J New Mater Electrochem Syst. 2021;24(1):21–8.
33. Nazhipkyzy M, et al. Activated carbon derived from cucumber peel for use as a supercapacitor electrode material. Nanomaterials. 2024;14(8):686.
34. Schütter C, et al. Casein-derived activated carbon: turning expired milk into active material for electrochemical capacitors. Energy Technol. 2020;8(3):1901225.
35. Ng C, et al. Activated carbon from pecan shell: process description and economic analysis. Ind Crops Prod. 2003;17(3):209–17.
36. Ramirez-Castro C, et al. Microporous carbonaceous materials prepared from biowaste for supercapacitor application. Electrochim Acta. 2016;206:452–7.
37. Wong S, et al. Recent advances in applications of activated carbon from biowaste for wastewater treatment: a short review. J Clean Prod. 2018;175:361–75.
38. Goh SMX, et al. Harnessing bamboo waste for high-performance supercapacitors: a comprehensive review of activation methods and applications. J Energy Storage. 2025;105:114613.
39. Azeez MA, Orege JI, Bamboo, its chemical modification and products. Bamboo-current and future prospects, 2018: p. 25–48.
40. Shen W, Fan W. Nitrogen-containing porous carbons: synthesis and application. J Mater Chem A. 2013;1(4):999–1013.
41. Basha DB, et al. Recent advances on nitrogen doped porous carbon micro-supercapacitors: new directions for wearable electronics. J Energy Storage. 2023;60:106581.

42. Al Haj Y, et al. Biowaste-derived electrode and electrolyte materials for flexible supercapacitors. Chem Eng J. 2022;435:135058.
43. Deng L, et al. In situ N-, P-and Ca-codoped biochar derived from animal bones to boost the electrocatalytic hydrogen evolution reaction. Resour Conserv Recycling. 2021;170:105568.
44. Koroglu D, Bingol H, Uralcan B. Flexible solid-state supercapacitors based on biowaste-derived activated carbon and nanomaterials for enhanced performance. Nanotechnology. 2025;36(10):105402.
45. Yang D, Ionescu MI. Metal oxide–carbon hybrid materials for application in supercapacitors. In: Metal Oxides in supercapacitors. Elsevier; 2017. p. 193–218.
46. Zekenova A, et al. Advances of biowaste-derived porous carbon and carbon–manganese dioxide composite in supercapacitors: a review. Inorganics. 2022;10(10):160.
47. Barton S, et al. Acidic and basic sites on the surface of porous carbon. Carbon. 1997;35(9):1361–6.
48. Montes-Morán M, et al. On the nature of basic sites on carbon surfaces: an overview. Carbon. 2004;42(7):1219–25.
49. Ahmed S, Ahmed A, Rafat M. Impact of aqueous and organic electrolytes on the supercapacitive performance of activated carbon derived from pea skin. Surf Coat Technol. 2018;349:242–50.
50. Chen Y, Wang X, Wang X Recent Advances in Biomass Waste Derived Carbon Materials for Supercapacitors: A Review. Energy Technology, 2024: p. 2301436.
51. Ali GA, et al. CaO impregnated highly porous honeycomb activated carbon from agriculture waste: symmetrical supercapacitor study. J Mater Sci. 2019;54:683–92.
52. Rufford TE, et al. Nanoporous carbon electrode from waste coffee beans for high performance supercapacitors. Electrochem Commun. 2008;10(10):1594–7.
53. Guo Y, et al. Preparation of supercapacitor carbon materials from food waste via low-temperature pyrolysis. J Anal Appl Pyrolysis. 2023;170:105880.
54. Le PA, et al. Abundant agricultural biomass wastes-derived 3D porous carbon material for high performance supercapacitors. Appl Nanosci. 2023;13(6):3827–38.
55. Wei X, et al. High performance hierarchical porous carbon derived from waste shrimp shell for supercapacitor electrodes. J Energy Storage. 2023;62:106900.
56. Singh A, Ojha AK. Orange peel derived activated carbon for supercapacitor electrode material. J Mater Sci Mater Electron. 2023;34(11):1003.
57. Kumar R, et al. Highly porous activated carbon prepared from the bio-waste of yellow mustard seed for high-capacity supercapacitor applications. Mater Chem Phys. 2023;304:127869.
58. Navaneethan D, Krishna S. Physicochemical synthesis of activated carbon from Canna indica (biowaste) for high-performance supercapacitor application. Res Chem Intermed. 2023;49(4):1387–403.
59. Jha MK, et al. Development of activated carbon from bhang (Cannabis) stems for supercapacitor electrodes. Mater Lett. 2023;344:134436.
60. Dhakal G, et al. Litchi seed biowaste-derived activated carbon supporting matrix for efficient symmetric and asymmetric supercapacitors. Carbon. 2023;208:277–89.
61. Nanda OP, et al. Bio-waste derived self-templated, nitrogen self-doped porous carbon for supercapacitors. Bioresour Technol Rep. 2022;19:101198.
62. Abdisattar A, et al. The impact of biowaste composition and activated carbon structure on the electrochemical performance of supercapacitors. Molecules. 2024;29(21):5029.
63. Yang I, et al. Improvement of a commercial activated carbon for organic electric double-layer capacitors using a consecutive doping method. Carbon. 2020;160:45–53.
64. Tu J, et al. American ginseng biowaste-derived activated carbon for high-performance supercapacitors. Int J Electrochem Sci. 2023;18(2):16–24.
65. Devi R, et al. Development of activated carbon by bio waste material for application in supercapacitor electrodes. Mater Lett. 2023;335:133830.
66. Jafari M, Botte GG. Sustainable green route for activated carbon synthesis from biomass waste for high-performance supercapacitors. ACS Omega. 2024;9(11):13134–47.
67. Michael M, Surya K. Feasibility study on conversion of biowaste of lemon peel into carbon electrode for supercapacitor using $ZnCl_2$ as an activating agent. Mater Renew Sustain Energy. 2024;13(3):409–20.
68. Surya K, Michael M. Hierarchical porous activated carbon prepared from biowaste of lemon peel for electrochemical double layer capacitors. Biomass Bioenergy. 2021;152:106175.
69. Mukhiemer S, et al. Physically and Chemically Activated Carbon from Coffee Waste in High Performance Supercapacitor Electrodes. 2024.
70. Tetra ON, et al. Preparation of activated carbon from corn stalks by dehydration method as supercapacitor electrode material. Iran J Chem Chem Eng. 2024;43(12):4348–59.
71. Dwiyaniti M, et al. Electrochemical characteristics of sugarcane bagasse-activated carbon as cathode material of lithium-ion capacitors. J Appl Res Technol. 2023;21(4):571–80.
72. Saha P, et al. Harnessing the power of marine biomass-derived carbon for electrochemical energy storage. Battery Energy. 2024. https://doi.org/10.1002/bte2.20240055.
73. Gnawali CL, et al. Nanoporous activated carbon material from Terminalia chebula seed for supercapacitor application. C. 2023;9(4):109.
74. Sivasankarapillai VS, et al. Hierarchical porous activated carbon derived from Callistemon viminalis leaf biochar for supercapacitor and methylene blue removal applications. ES Energy & Environment. 2024;24:1124.
75. Magar SD, et al. Brewery waste derived activated carbon for high performance electrochemical capacitors and lithium-ion capacitors. Electrochim Acta. 2023;446:142104.
76. Xiong Ca, Wang N, Feng M. Activated carbon derived from waste oil shale semi-coke for supercapacitor application. Molecules. 2023;28(12):4804.
77. Taer E, et al. A green and low-cost of mesoporous electrode based activated carbon monolith derived from fallen teak leaves for high electrochemical performance. J Appl Eng Sci. 2021;19(1):162–71.
78. Huarote-Garcia E, et al. Activated carbon electrodes for supercapacitors from purple corncob (Zea mays L.). ACS Environ Au. 2024;4(2):80–8.

79. Mondal M, Goswami DK, Bhattacharyya TK. Lignocellulose based bio-waste materials derived activated porous carbon as superior electrode materials for high-performance supercapacitor. J Energy Storage. 2021;34:102229.
80. Akdemir M. Electrochemical performance of Quercus infectoria as a supercapacitor carbon electrode material. Int J Energy Res. 2022;46(6):7722–31.
81. Jayachandran M, et al. Activated carbon derived from bamboo-leaf with effect of various aqueous electrolytes as electrode material for supercapacitor applications. Mater Lett. 2021;301:130335.
82. Taer E, et al. Three-dimensional pore structure of activated carbon monolithic derived from hierarchically bamboo stem for supercapacitor application. Commun Sci Technol. 2020;5(1):22–30.
83. Hayashi S, et al. Laser upcycling of hemoglobin protein biowaste into engineered graphene aerogel architectures for 3D supercapacitors. Adv Sci. 2025;12(8):2412588.
84. Goswami S, et al. Biowaste-derived carbon black applied to polyaniline-based high-performance supercapacitor microelectrodes: sustainable materials for renewable energy applications. Electrochim Acta. 2019;316:202–18.
85. Ma D, et al. Oxygen-enriched hierarchical porous carbon derived from biowaste sunflower heads for high-performance supercapacitors. RSC Adv. 2015;5(130):107785–92.
86. De Souza LK, et al. Hierarchical porous carbon derived from acai seed biowaste for supercapacitor electrode materials. J Mater Sci: Mater Electron. 2020;31:12148–57.
87. Wen Y, et al. Nitrogen/oxygen enriched hierarchical porous carbons derived from waste peanut shells boosting performance of supercapacitors. Adv Electron Mater. 2020;6(10):2000450.
88. Gaona-Torres S, et al. Carbon fibers from banana trunk biowaste coated with metallic nanoparticles as electrode material. Biomass Convers Biorefin. 2024;14(22):28797–806.
89. Khalafallah D, et al. La/Sn dual pseudo-active sites stabilized biowaste Chinese bitter melon-derived locally graphitized hierarchical porous carbons for $VOSO_4$ redox-enhanced supercapacitors. J Energy Storage. 2025;110:115343.
90. Fan K, et al. Preparation of carbon electrode material with a large specific surface area and multiscale pore structure from biowaste kochia for symmetrical supercapacitor. Energy Technol. 2023;11(4):2201281.
91. Thilageshwaran S, et al. Electrochemical study on Activated Carbon Electrode from Kenaf biowaste for Supercapacitor Application. in 2020 International Conference and Utility Exhibition on Energy, Environment and Climate Change (ICUE). 2020. IEEE.
92. Stojanovska E, et al. Solution blown polymer/biowaste derived carbon particles nanofibers: an optimization study and energy storage applications. J Energy Storage. 2019;26:100962.
93. Reddy NP, et al. Biowaste-derived hierarchical activated porous carbon with heteroatom-doping (N/S) for efficient symmetrical supercapacitors: a cow urine approach. J Energy Storage. 2025;115:115964.
94. Tan Y, et al. Highly graphitized porous carbon prepared from biomass waste sunflower shells for supercapacitors. J Electron Mater. 2023;52(4):2603–13.
95. Bigdeloo M, et al. Activated carbon derived from fennel flower waste as high-efficient sustainable materials for improving cycle stability and capacitance performance of electroactive nanocomposite of conductive polymer. J Energy Storage. 2022;55:105793.
96. Dubey P, et al. Electrolytic study of pineapple peel derived porous carbon for all-solid-state supercapacitors. ChemSelect. 2021;6(42):11736–46.
97. Nkele AC, et al. Recent advances in materials for supercapacitors. Nano-Horizons, 2022. **1**(1).
98. Zhang L, et al. Biomass-derived materials for electrochemical energy storages. Prog Polym Sci. 2015;43:136–64.
99. Wang R, et al. Towards the sustainable production of biomass-derived materials with smart functionality: a tutorial review. Green Chem. 2024. https://doi.org/10.1039/D4GC01771D.
100. Yu X, et al. Universal mass production of biomass-derived nanosized porous carbon spheres as a superior nonmetal catalyst for aerobic oxidation of hydrocarbons. ACS Sustain Chem Eng. 2022;10(45):14735–45.

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