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# A Review on Carbon Materials Derived from Biomass Pyrolysis for Supercapacitor Applications

**Fitri Handayani Hamid [1,*], Kurnia Sri Yunita [1], Mashuni Mashuni [2], M Jahiding [3], Erzam S Hasan [4]**

[1] Department of Chemistry, Institute of Science Technology and Health 'Aisyiyah Kendari, Kendari, Indonesia
[2] Department of Chemistry, Halu Oleo University, Kendari, Indonesia
[3] Department of Physics, Halu Oleo University, Kendari, Indonesia
[4] Department of Geophysical Engineering, Halu Oleo University, Kendari, Indonesia
*Email (corresponding author): fitrihandayanihamid@gmail.com

***Abstract.*** *Carbon-based materials are solid carbon enriched with carbon, produced through thermochemical processes such as pyrolysis. However, unmodified and unactivated carbon materials obtained from low-temperature pyrolysis of biomass show poor performance in energy storage applications due to their unsuitable physicochemical and electrical properties, such as low surface area, inadequate pore structure, and low density and conductivity. To improve the properties of carbon, surface modification and activation are applied to enhance carbon's surface features and structure, resulting in better electrochemical performance. Various activation methods are used to modify the surface properties of carbon, making it more suitable for supercapacitor applications. This review provides a comprehensive overview of carbon activation techniques, focusing on their effects on physicochemical and electrical properties and their potential use as supercapacitor electrodes. The article also highlights existing research gaps and suggests directions for future development.*

***Keywords:*** *Biomass, carbon, pyrolysis, supercapacitor*

## 1. Introduction

The increasing global climate change and limited fossil fuel resources are driving the world to shift to cleaner and more sustainable renewable energy sources. Although renewable energy offers an environmentally friendly solution, the problem of intermittency or irregularity of energy supply is often a constraint, which necessitates the development of efficient energy storage systems. The most widely used energy storage system is secondary batteries, which have high energy density but low power and are prone to capacity degradation and limited cycle life. In contrast, supercapacitors have emerged as a promising alternative for energy storage with high power capacity, long cycle life, and fast charging efficiency. However, supercapacitors are still limited by lower energy density than conventional batteries, as well as high series resistance and cost. To evaluate the performance of supercapacitors, the basic elements related to electrodes and electrolytes are essential (Dar et al., 2024; J. Zhang et al., 2023). Stable, long-lasting, and electrically conductive electrode materials can enhance the electrodes' highly desired capacitive performance. The surface's wetting characteristics are also essential when creating electrode materials.


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Carbon compounds from biomass have favourable physicochemical characteristics, such as high surface area, porosity, electrical conductivity, and minerals and metal ions necessary for electrochemical reactions. These features are ideal for supercapacitor applications (Saini et al., 2021; Zhai et al., 2022; H. Zhang et al., 2023). Biomass-derived carbon has drawn more interest because of its plentiful natural sources, eco-friendliness, and distinctive porous characteristics. These qualities make it a perfect material for many uses, especially in energy conversion and storage devices like supercapacitors (Chen et al., 2012; Dar et al., 2024; Januszewicz et al., 2020; M. Zhang et al., 2023). Biomass sources, such as rice husks, coconut shells, and other materials, offer cheap, plentiful, and sustainable carbon resources (Barakat et al., 2022; Taer et al., 2018). Energy applications make substantial use of carbon-based materials, including carbon nanotubes, graphene, and activated carbon. By boosting energy storage capacity, efficiency, and durability, they improve the performance of fuel cells, photovoltaics, lithium-ion batteries, and supercapacitors. Furthermore, these materials facilitate efficient hydrogen storage, energy harvesting, and water treatment through capacitive deionization, offering sustainable solutions across various energy sectors (Lobato-Peralta et al., 2024; Senthil & Lee, 2021). In contrast, traditional carbon materials derived from non-renewable resources often require harsh production conditions and more complex synthesis methods (Deng, Li, et al., 2016; Garg et al., 2017). Therefore, employing environmentally friendly production methods that utilize sustainable raw materials to synthesize carbon materials is essential.

Lignocellulosic biomass, with a carbon content of around 45-50 wt%, is a promising raw material for producing carbon-based biochar (Deng, Li, et al., 2016). Lignocellulose composition varies depending on the plant species and part used. However, cellulose is generally the most abundant major component, followed by hemicellulose and lignin (Deng, Xiong, et al., 2016). Biomass pyrolysis is a thermochemical process that converts biomass—consisting of cellulose, hemicellulose, and lignin—into valuable products such as biochar, bio-oil, and non-condensable gases. This process occurs by heating biomass without oxygen between 300°C and 700°C. This process allows the decomposition of materials at temperatures below 500°C, producing products that can be utilized for energy, fuel, and various material applications. Cellulose and hemicellulose decompose at lower temperatures, while lignin affects the stability and structure of the final product (Chu et al., 2018). In addition, biomass pyrolysis also opens up opportunities to produce carbon materials that can be further modified with metal oxides to improve energy storage capacity and cycle stability. Therefore, this article aims to provide an updated review of the potential of biomass as a source of carbon materials for energy storage applications, especially in supercapacitors. The primary focus of this article is carbon production through biomass pyrolysis, carbon surface modification, and the application of metal oxides to improve electrode performance. By understanding the relationship between carbon structure and electrochemical performance, it is hoped that solutions can increase supercapacitors' energy density and power while reducing production costs and environmental impacts.

## 2. Overview of Biomass Pyrolysis for Carbon Production

Biomass pyrolysis is a thermochemical process that decomposes biomass materials at elevated temperatures in an oxygen-limited environment to produce carbon-based products (Pahnila et al., 2023; Rambhatla et al., 2025). The possibility of producing high-value carbon products like biochar, activated carbon, and graphene—which have a variety of uses in material science, energy storage, and environmental remediation—has drawn much attention to this technology. These carbon compounds are highly valued for their stability, porosity, and large surface area, which makes them perfect for water filtration systems, batteries, and supercapacitors (Saini et al., 2021).

Biomass pyrolysis involves heating organic materials (e.g., agricultural residues, wood) to 350–800°C in an oxygen-free environment, breaking down complex polymers like cellulose and lignin into simpler compounds. Key variables include:

- **Temperature**: Lower temperatures (350–450°C) favor biochar production, while higher temperatures (500–700°C) maximize bio-oil or syngas yields.
- **Heating rate**: Slow heating (minutes to hours) enhances biochar formation, whereas rapid heating (seconds) prioritizes bio-oil.
- **Residence time**: Longer gas residence times promote secondary reactions, increasing gas yields.

The final carbon's form, porosity, and usefulness are influenced by several intricate processes that biomass goes through during the pyrolysis process. By heating biomass without oxygen, the primary constituents of biomass—cellulose, hemicellulose, and lignin—are broken down in the pyrolysis process, known as lignocellulose degradation. Between 300°C and 350°C, cellulose starts to break down, releasing gas, bio-oil, and a tiny quantity of biochar. The more easily broken-down hemicellulose breaks between 200°C and 300°C, producing highly acidic gas and bio-oil. At temperatures between 350°C and 500°C, lignin, which is more complex and stable, breaks down to produce denser biochar, aromatic bio-oil, and non-condensable gases (X. Lu & Gu, 2022; Pahnila et al., 2023). This process is regulated by temperature and biomass composition, allowing for the creation of biochar, bio-oil, and gas that can be used in many applications. The pyrolysis process can be optimized by adjusting operating conditions such as heating rate, temperature, and residence time to produce the desired product, with low temperatures and long residence times (slow pyrolysis) favouring char production, while higher temperatures and short residence times (fast pyrolysis) increase oil yield. Stable biochar with a high carbon content (50–90%) is produced via slow pyrolysis, which is suited for carbon production. Although the focus is on bio-oil, biochar is a byproduct of fast pyrolysis (Azeta et al., 2021; Raza et al., 2021).

**Table 1**. Types of pyrolysis

| Type | Conditions | Primary Product | Yield Characteristics |
|---|---|---|---|
| Slow | Low heating rate, <500°C | Biochar | 30-35% biochar, 30% liquids |
| Fast | High heating rate, ~500°C | Bio-oil | 60-70% bio-oil, 15% biochar |
| Flash | Ultra-rapid heating, >700°C | Syngas | Maximizes gas production |

Biomass pyrolysis is considered a sustainable method, providing an alternative to fossil-based carbon production. Carbon, a key product of biomass pyrolysis, is especially valued for its potential in soil enrichment and carbon sequestration. The carbon efficiency in the process can reach significant levels, making it a promising tool for reducing atmospheric $CO_2$ (Schmidt et al., 2019). Pyrolysis also helps in reducing the environmental impact of biomass by converting waste into useful products, contributing to both carbon neutrality and waste management (Yu et al., 2022).

Biomass pyrolysis holds significant potential, but controlling the process to maximize the yield of specific carbon materials remains challenging. Innovations like microwave-assisted pyrolysis and catalytic pyrolysis are being explored to improve the efficiency and tailor the properties of the products (H. Zhang et al., 2023). Electrodes for supercapacitor applications have been developed using carbon-based materials sourced from various biomass sources, including wood, crop residues, agro-waste, and industrial biomass by-products (H. Lu & Zhao, 2017; Zhu et al., 2025). Supercapacitor electrodes are made of carbon materials from various biomass sources, including wood and agricultural waste, because of their favourable physicochemical characteristics, high surface area, robust stability, and superior electrical conductivity (Zhu et al., 2025). Achieving the ideal surface area and pore structure is still tricky (Li et al., 2024; H. Liu et al., 2023). Supercapacitors' performance is being enhanced by applying surface modification and activation techniques.

## 3. Plant Biomass as a Carbon Source

Many biomaterials made from biomass have been used as carbon sources. According to Saleh (2024), biomass is any organic material derived from plants or other organic waste that may be thermally processed, such as pyrolysis or carbonization, to produce carbon (Saleh, 2024). To support the application of supercapacitors and electrical double-layer capacitors (EDLC), research on carbon from plant biomass has focused on finding biomass precursors with high carbon content, hierarchical nanoporous structures, and heteroatom compositions that encourage the formation of interconnected meso/micropore structures and surface functional groups containing N/O during the carbonization/activation process (Zhu et al., 2025). Therefore, to create biochar with the best supercapacitive qualities, it is essential to research and comprehend the properties of biomass. The quantitative chemical composition of plant-based biomass generally differs between species; it can even vary quantitatively within the same plant's various parts. Despite coming from a variety of species, plant-based biomass usually contains similar components including lignin, cellulose, and hemicellulose in its qualitative chemical composition. **Table 2** displays the representative lignocellulose composition of biomass derived from plants.

The biomass carbonization process produces activated carbon with a porous structure, making it ideal for supercapacitor applications. This material can store large amounts of energy and release it quickly. Utilizing biomass as a carbon source enhances sustainability by leveraging agricultural waste, which helps minimize waste and supports the growth of renewable energy. Biomass offers an efficient, affordable, and eco-friendly approach to producing supercapacitors, aiding in advancing sustainable energy storage solutions. During the carbonization process, plant-derived biomass is transformed into carbon, and the carbon yield is primarily determined by its chemical composition, especially the amounts of lignin, cellulose, and hemicellulose (Atika & Dutta, 2024; Teng et al., 2025). Lignin, with the highest thermal stability, contributes significantly to char and activated carbon yields, while the less stable cellulose and hemicellulose provide only low to moderate amounts of carbon (C. Zhang et al., 2024). Therefore, plant-based biomass with a high lignin fraction, low cellulose, low oxygen, and high nitrogen content is recommended for producing carbon with a high yield, better gravity, and optimal conductivity, which are essential for high-performance supercapacitor materials (Y. Liu et al., 2018).

**Table 2**. Lignocellulose compositions of plant-based biomass

| Biomass | Moisture (%) | Lignin (%) | Cellulose (%) | Hemicellulose (%) | References |
|---|---|---|---|---|---|
| Coconut coir | 13.68 | 46.48 | 21.46 | 12.36 | (Arsene et al., 2013) |
| Coconut sheath | 5.90 | 29.7 | 31.05 | 19.22 | |
| Bagasse | 5.64 | 22.56 | 39.45 | 26.97 | |
| Banana leaf | 11.69 | 24.84 | 25.65 | 17.04 | |
| Corn stover | - | 18-22 | 37-42 | 20-28 | (Khan et al., 2021) |
| Rice straw | - | 10-18 | 32-41 | 15-24 | (Lo et al., 2021) |
| Palm shell | - | 53.4 | 29.7 | - | (Daud, 2004) |
| Empty Oil Palm Fruit Bunches | 3.74 | 16.49 | 45.95 | 22.84 | (Hossain et al., 2016) |
| Cocoa pod husk | 11.04 | 50.68 | 49.06 | 19.06 | (Hozman-Manrique et al., 2023) |
| Sago dregs | 11.68 | 9.7-21 | 36.3–39.5 | 14.6–17.9 | (Hammado et al., 2020) |

Biomass such as coconut coir, cocoa pod husk, and empty oil palm fruit bunches show significant potential as carbon sources for supercapacitors. Biomass with low moisture content, like empty oil palm fruit bunches (3.74%) and bagasse (5.64%) (Alokika et al., 2021; Hossain et al., 2016), is more efficient in the carbon conversion process because it requires less energy for drying, making it more economical. The high lignin content in cocoa pod husk (50.68%) provides a strong structure to the resulting carbon (Hozman-Manrique et al., 2023). In comparison, the high cellulose content in cocoa pod husk (49.06%) and empty oil palm fruit bunches (45.95%) enables the production of porous carbon that is highly effective in energy storage (Hossain et al., 2016; Hozman-Manrique et al., 2023). Additionally, biomass with relatively high hemicellulose content, such as bagasse (26.97%) and corn stover (20-28%), accelerates the carbon conversion process (Alokika et al., 2021; Khan et al., 2021), crucial for enhancing supercapacitor performance.

The choice of biomass type as a precursor is greatly influenced by local availability, cost, and chemical composition. For example, sugarcane bagasse and rice husk have been shown to produce activated carbon with a large surface area and good adsorption capacity for dyes and heavy metals (Chew et al., 2023). Other agricultural and forestry wastes are also widely used because of their lignocellulosic properties, which are suitable for producing activated carbon with pore characteristics that can be adjusted through activation processes (Gayathiri et al., 2022; Iwanow et al., 2020). Using various biomass as raw materials for activated carbon supports sustainable waste management while providing functional materials for environmental and energy applications, such as water filtration, energy storage, and supercapacitors (Gayathiri et al., 2022; Neme et al., 2022).

## 4. Activation of Carbon Materials Derived from Biomass

It is necessary to develop new materials that improve supercapacitor performance to meet the needs of future technologies, such as flexible, portable electronics and hybrid electric vehicles. Among carbon-based materials, activated carbon is notable for its controllable porous structure, chemical stability, high electrical conductivity, and extensive use in supercapacitor devices, comprising nearly 80% of production (Suhas et al., 2017). The performance of these materials depends on the choice of biowaste precursor and the activation method used, which determines factors such as surface area, pore size distribution, functional group composition, and overall electrode performance. Two main activation methods for biomass-based carbons are commonly used, and this section will discuss the supercapacitive properties of various biowaste materials.

Carbon-based materials obtained directly through pyrolysis typically have poor surface characteristics and lower surface area (Parveen et al., 2017). Essential properties for electrochemical applications, such as high energy density and fast charge/discharge rates, can be improved by activation, enhancing activated carbon's surface features. Carbon activation consists of two steps: first, pyrolyzing the selected biomass, and second, modifying the surface through activation. Pyrolysis results in carbon with an underdeveloped pore structure and a stable framework, which can be restructured using chemical or physical activation methods (Sundriyal et al., 2021).

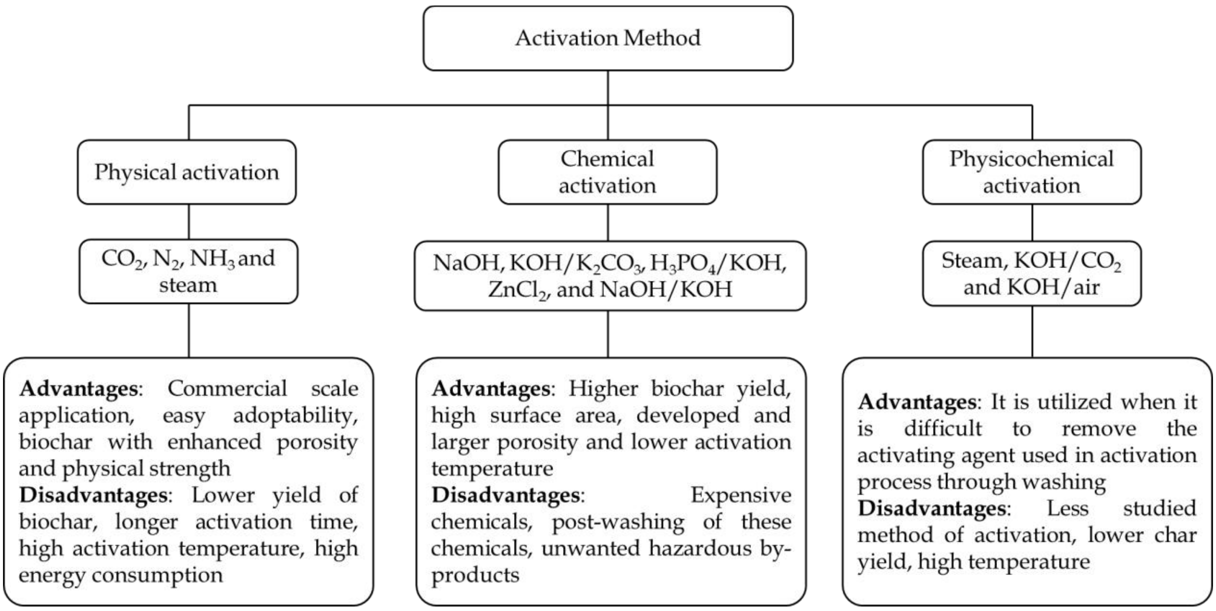


**Figure 1**. Types of activation methods (Mehdi et al., 2022)

The activation process can be carried out using physical and chemical activation. Physical activation involves heating biomass carbon at high temperatures (500–900°C) in the presence of gases such as steam or carbon dioxide to create pores and increase surface area. In contrast, chemical activation involves soaking biomass in an activation agent, such as an acid or base, before heating it at a lower temperature (300–600°C) to produce more controlled porosity. Both methods produce activated carbon with an ideal pore structure for energy storage and adsorption applications while promoting sustainability by utilizing agricultural waste. Additionally, physicochemical activation offers another approach to modify the carbon surface and enhance the properties of activated carbon. This method, which can involve physical, chemical, or a combination of both processes, has been shown in several studies to improve the morphology and performance of activated carbon, particularly in supercapacitors, by creating effective surface characteristics (Januszewicz et al., 2020; Taer et al., 2014). Figure 1 presents a summary of the three activation methods: physical, chemical, and physicochemical activation.

### 4.1. Chemical Activation

In contrast to physical activation, chemical activation of carbon involves treating biomass with a chemical activating agent, such as potassium hydroxide (KOH), zinc chloride ($ZnCl_2$), or phosphoric acid ($H_3PO_4$), and then heating the biomass to comparatively lower temperatures (300–600°C). This process typically involves two main stages: impregnation and heating. In the impregnation stage, biomass is soaked in the chemical agent, which breaks down the biomass structure and opens up its pores. In order to start chemical reactions that result in a highly porous carbon structure, the biomass is heated in an inert atmosphere (such as nitrogen or argon) after impregnation. After combining biomass with an activation agent, it is calcined at high temperatures to complete the activation process. The biomass and activation agent are mixed in an ideal ratio to get the desired properties and then activated at high temperatures. The activation agents, including bases, acids, or salts, are incorporated into the biomass through physical mixing and stirring. The electrochemical performance of activated carbon largely depends on the activation conditions, precursor materials, and final material structure. In certain instances, pyrolysis is used to manufacture carbon obtained from biomass, and activated carbon is subsequently created by heating the impregnated char in a nitrogen environment.

For instance, carbon extracted from chestnuts is created and activated through a post-treatment procedure, which may be employed as an electrode material for energy storage applications (Januszewicz et al., 2020). By hydrothermally carbonizing hydrochar and then thermochemically activating it with $H_2PO_4$, $ZnCl_2$, and KOH-activated at 600°C, corncob biomass can be transformed into activated carbon with changed surface properties (Sarwar et al., 2021). According to a study by Kiełbasa et al., the following activation agents are utilized for carbon activation: HCl, NaOH, KOH, $H_2SO_4$, and $H_3PO_4$ (Kiełbasa et al., 2022). In a study by Barakat et al., the combination of $H_3PO_4$/KOH was proposed as an effective activation agent for producing activated carbon from rice husk (Barakat et al., 2022). A study by Demir and Doguscu reported NaOH, $K_2CO_3$ town-centre, $Na_2CO_3$ town-centre, and $Na_2S_2O_3$ town-centre as activation agents (Demir & Doguscu, 2022).

In chemical activation methods, selecting activation agents is crucial in determining the properties of biomass-derived carbon. KOH, in particular, offers significant advantages in achieving high yields with well-controlled pore structures, including micropores, mesopores, and large specific surface areas, even at lower temperatures. KOH activation typically involves an initial heat treatment followed by the activation process. Various types of biomass have been used to produce carbon, which is then activated with KOH or NaOH. These activated carbons are commonly utilized in supercapacitor applications. The physical properties of porosity can be explained through the following steps: First, the oxidants oxidize carbon into carbonate ions. Next, the leaching of metal compounds further increases the pore size. Finally, $M_2CO_3$ decomposes into CO or $CO_2$, further expanding the pores. The general reaction scheme for chemical activation using alkali is represented by equations (1)–(4), where M refers to alkali metals such as K or Na (Dehkhoda et al., 2016).

$$2MOH + CO_2 \rightarrow M_2CO_3 + H_2O\uparrow \quad (1)$$

$$2C + 2MOH \rightarrow 2CO\uparrow + 2M\uparrow + H_2 \quad (2)$$

$$M_2CO_3 + C \rightarrow M_2O + 2CO\uparrow \quad (3)$$

$$M_2O + C \rightarrow 2M\uparrow + CO\uparrow \quad (4)$$

### 4.2. Physical Activation

The first stage of physically activating carbon is called carbonization, and it entails heating biomass without oxygen between 400°C and 700°C. This process breaks down the organic material, releasing volatile components and producing a carbon-rich char. The carbonized biomass is exposed to an activating gas, like carbon dioxide or steam, at higher temperatures—typically between 800°C and 1000°C—during the second phase, activation. This activation significantly increases the material's surface area and enhances its energy storage, adsorption, and supercapacitor properties by creating a highly porous structure. Excellent surface properties are produced, making the activated carbon perfect for various industrial and environmental uses. Research on employing $CO_2$ as an activation agent to turn lignocellulosic biomass—like hybrid willow—into activated carbon has produced noteworthy outcomes (Cuong et al., 2019; Mehdi et al., 2022). With a current density of 100 mA/g, the maximum specific capacitance of 92.7 F/g was attained. A maximum surface area of 738.74 $m^2/g$ was achieved under ideal activation circumstances, which included a temperature of 800°C and a residence time of 60 minutes (Jiang et al., 2020). Usually, air is used for this process at lower temperatures, whereas steam and $CO_2$ are used at temperatures between 700°C and 1100°C (T. Zhang et al., 2004).

However, temperatures beyond 1200°C can collapse the pore structure, produce ash and reduce carbon output. By encouraging pore formation, the devolatization process raises the carbon capacity. Although this activation method is easy to use and eco-friendly, careful control of temperature, speed, and duration is necessary for optimum results. Since the activation temperature and time significantly impact the carbon produced using this approach, it is imperative to carefully manage them to get the appropriate surface characteristics and functional groups (Olorundare et al., 2014). Equations (5)–(7) explain how the reaction between carbon and $H_2O$ or $CO_2$ during physical activation causes the loss of carbon atoms and the creation of pores (Qian et al., 2020).

$$C + CO_2 \rightarrow 2CO \quad (5)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (6)$$

$$C + H_2O \rightarrow H_2 + CO \quad (7)$$

### 4.3. Physiochemical Activation

The physicochemical activation method is a technique that merges both physical and chemical processes to activate carbon. It involves treating the precursor material or char with an activation agent and pyrolysis in a reactor with an oxidizing agent to produce the activated material (Ooi et al., 2017). This approach is used when the activation agent is tricky to remove through washing, which could result in pore blockage. Some challenges of this method include high temperatures, prolonged processing times, and lower yields. For instance, using $CO_2$ activation at 800°C on activated carbon made from coconut shells and palm stones with KOH or $ZnCl_2$, Hu et al. investigated the combined effects of various activation techniques to generate high mesoporosity (Hu et al., 2003). Furthermore, the production of activated carbon from coffee grounds using physical, chemical, and combination activation techniques has been investigated. Activated carbon was produced by E. Taer et al. using sugarcane bagasse as a precursor and physicochemical and physical activation techniques (Taer et al., 2014).

Due to its dual activation process, physicochemical activation is less frequently studied for supercapacitor applications; nonetheless, it is still involved in producing activated carbon. As illustrated in Figure 1, activated carbon is produced using various activation techniques, such as physical, chemical, and physicochemical, each with pros and cons for uses like energy storage.

## 5. Application Activated Carbon for Supercapacitor Electrodes

Biomass-derived activated carbon has drawn much interest as a perfect material for supercapacitor applications because of its unique qualities, abundance, and affordability. Numerous research studies have investigated various biomass sources, including date palm seeds (Ahmad et al., 2023), rice husks, walnut shells (Taurbekov et al., 2023), corn husks (Macherla et al., 2025; Xiang et al., 2024), coconut shells (Taer et al., 2018; Zhao et al., 2023), and oil palm empty fruit bunches (EFBs) (Arundina et al., 2025; Dieu et al., 2021; Rustamaji et al., 2022), to create activated carbon with improved electrochemical performance. These studies compare different activation strategies, such as chemical activation using KOH and physical activation using $CO_2$, to assess the resulting supercapacitors' specific capacitance, cycle stability, and energy storage efficiency. The following table summarizes the findings of these studies and identifies the specific capacitances and critical performance metrics of biomass-based activated carbons intended for use in supercapacitors (**Table 3**).

Physical and chemical activation techniques were also used to create coffee-derived activated carbon from discarded coffee grounds. This material performed exceptionally well for energy storage, exhibiting a specific capacitance of 84 F/g at 1 A/g and maintaining 70% of its capacitance at 10 A/g after 5000 charge-discharge cycles (Adan-Mas et al., 2021). Lastly, hybrid supercapacitors that combine activated carbon from biomass with battery-type materials like MnS and graphene oxide were investigated for improved electrochemical performance. These hybrid systems demonstrated high energy and power densities, with the MnS/graphene oxide hybrid material showing remarkable capacitance and stability, highlighting the potential of biomass-derived carbons in next-generation supercapacitors (Alzaid et al., 2021).

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**Table 3**. Research studying carbon derived from biomass as an ideal material for supercapacitor applications

| Study | Biomass Source | Activation Method | Specific Capacitance (F/g) | Cycle Stability | Surface Area (mÂ$^2$/g) | Remarks |
|---|---|---|---|---|---|---|
| Ahmad et al. (2023) | Date palm seed | Physical activation with $CO_2$ | 138.12 at 5 mV/s | 1000 cycles at 2 mV/s, 30,000 cycles at 10 mV/s | 738.74 | New KOH-free activation method |
| Taurbekov et al. (2023) | Rice husk, Walnut shell | $CO_2$, activation vs. KOH activation | 157.8 for rice husk, 152 for walnut shell | 80% retention for rice husk, 75.6% for walnut shell at high currents | Not mentioned | $CO_2$, activation is more efficient and environmentally friendly |
| Xiang et al. (2024) | Corn husk | KOH activation after carbonization | 413.4 at 0.5 A/g | Not mentioned | 1103 | High specific capacitance at low current density |
| Macherla et al. (2025) | Corn husk | Chemical activation with KOH | 133 at 1 A/g | 93.5% retention after 4500 cycles | 1583 | Excellent pore connectivity and high surface area |
| Zhao et al. (2023) | Coconut shell | KOH activation | 317 at 0.5 A/g | 68% retention at 20 A/g, 99.7% after 10,000 cycles | 2143.6 | Impressive cycle stability |
| Taer et al. (2018) | Coconut husk | Physical and chemical activation | 184 at 1 A/g | Not mentioned | 1033.2 | Significant surface area increases due to activation |



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| Study | Biomass Source | Activation Method | Specific Capacitance (F/g) | Cycle Stability | Surface Area (mÂ²/g) | Remarks |
|---|---|---|---|---|---|---|
| Dieu et al. (2021) | Oil palm EFB | Chemical activation with nitrogen doping | 182-217 at 0.5 A/g | Not mentioned | 2774 | Nitrogen doping enhanced capacitance |
| Arundina et al. (2025) | Oil palm EFB | Pyrolysis and activation methods | 389.122 at 1 A/g | Not mentioned | Not mentioned | Highest capacitance achieved through pyrolysis |
| Rustamaji et al. (2022) | Oil palm EFB | Hydrothermal carbonization with $CaCl_2$, urea impregnation, $CO_2$, activation | 176.76 at 2 mV/s | 98.7% after 5000 cycles | Not mentioned | High capacitance and energy densities |
| Adan-Mas et al. (2021) | Spent coffee grounds | Physical and chemical activation | 84 at 1 A/g | 70% retention at 10 A/g after 5000 cycles | Not mentioned | Good performance after long cycle life |
| Alzaid et al. (2021) | Hybrid (MnS/graphene oxide) | Hybrid supercapacitors (Biomass carbon + MnS/graphene oxide) | Varied (high performance) | High energy and power densities, excellent stability | Not mentioned | Hybrid systems demonstrated high electrochemical performance |

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## 6. Conclusions

Studies on biomass-derived activated carbon for supercapacitor applications have shown that it is a viable, cost-effective, and sustainable material. Activated carbon with remarkable electrochemical qualities has been created from various biomass sources, including date palm seeds, rice husks, corn husks, coconut shells, and oil palm empty fruit bunches. These materials are promising for supercapacitor applications because of their high specific capacitance, superior energy and power densities, and remarkable cycle stability. Although chemical and physical activation techniques have been effectively used, $CO_2$ activation is cost-effective and ecologically friendly to increase capacity retention. The findings emphasize the versatility of biomass as a renewable resource for carbon production, with specific capacitances ranging from 84 F/g to over 413 F/g. Moreover, these materials provide a sustainable alternative to conventional energy storage solutions by addressing waste management issues and supporting the development of clean energy technologies. However, optimizing activation processes—such as temperature, time, and activating agents—remains an ongoing research focus to improve performance and scalability. Looking ahead, combining biomass-derived activated carbon with other materials like graphene or MnS in hybrid supercapacitors could enhance energy and power densities, potentially advancing next-generation energy storage technologies. Scaling up production while maintaining cost-effectiveness and minimizing environmental impact will be key to the widespread adoption of biomass-based supercapacitors. Further investigation into long-term stability and real-world performance is critical for fully unlocking the potential of these materials in commercial supercapacitor technologies. Beyond supercapacitors, biomass-derived activated carbon also shows promise in other energy-related applications, such as batteries and environmental remediation, positioning it as a valuable resource in the expanding field of sustainable energy storage.

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## Conflicts of Interest

The authors declare no conflict of interest.

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