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Utilization of Biomass as a Source of Activated Carbon for Supercapacitor Applications: A Review

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Abstract
Research on activated carbon generated from biomass as a possible supercapacitor electrode material has increased in response to the growing need for sustainable energy storage solutions. Recent advancements in the synthesis, activation, and electrochemical performance of activated carbon derived from biomass are covered in this review. Carbonization and chemical activation employing agents like KOH, H_3PO_4, $ZnCl_2$, and $CaCl_2$ which have a major impact on pore structure and surface area are the usual steps in biomass activation. $CaCl_2$ activation creates mesoporous structures that facilitate rapid ion diffusion and enhanced capacitance, whereas KOH and $ZnCl_2$ activation often yield the largest surface area with dominant micropores. Electrochemical stability and electrical conductivity are further improved by nitrogen doping. The selection of electrolyte is also crucial; ionic liquid electrolytes, such EMIM-BF_4, offer greater thermal stability and broader voltage windows, while aqueous electrolytes, including H_2SO_4 and KOH, offer high capacitance because of their high ionic conductivity. Depending on the pore shape and activation technique, biomass-based carbons have been reported to have specific capacitances ranging from 250 to 450 F/g. All things considered, a successful method for creating high-performance, sustainable electrode materials for next-generation supercapacitors involves combining appropriate activation agents, heteroatom doping, and optimal electrolytes.

INTRODUCTION

The interest for alternative sustainable energy sources has driven intensive research into the development of high-performance energy storage devices, one of which is supercapacitors. Supercapacitors stand out compared to conventional batteries due to their high power density, long cycle life, and fast charging times (Haider et al., 2025). The performance of supercapacitors is highly dependent on the characteristics of the electrode material, especially activated carbon which has powerful electrical conductivity and significant specific surface area.(Y. Liu et al., 2021).

Activated carbon made from biomass have garnered a lot of scientific interest because of their affordability and adjustable specific surface area (Q. Fan et al., 2025). Biomass offers advantages due to its abundant availability, low cost, and potential to reduce organic waste and carbon emissions (Neme et al., 2022).

Furthermore, the use of biomass in activated carbon production supports the concept of a circular economy and integrated waste management (Nguyen et al., 2025). Commonly used biomass types include rice husks, coconut shells, coffee grounds, walnut shells, and other agricultural residues (Gillespie et al., 2025). Activated carbon from biomass is generally obtained through a carbonization process followed by activation using chemical or physical methods (Kumar & Tripathi, 2025). Chemical activation using agents such as KOH, H_3PO_4, and $ZnCl_2$ has been shown to be effective in producing materials with high porosity and large surface area (Yadav et al., 2023). Meanwhile, the hydrothermal carbonization method is an alternative because it is efficient for biomass with high moisture content without requiring an intensive drying stage (Gao et al., 2024).

Recent research trends point to the development of activated carbon–metal oxide composites such as NiO and MnO_2 to enhance the electrochemical performance of supercapacitors (Ba shbil et al., 2025). This combination combines the high conductivity of carbon with the redox activity of metal oxides, significantly increasing the specific capacitance and cycling stability (Zhu et al., 2025). However, although various synthesis and modification methods have improved supercapacitor performance, challenges remain in producing materials with optimal pore structure, long-term stability, and cost efficiency on an industrial scale (Wang et al., 2023). Furthermore, systematic comparative studies on biomass types, activation methods, and electrochemical yields are limited.

Therefore, this review aims to analyze and compare recent research results on the use of various biomass types as activated carbon sources for supercapacitor applications. The discussion focuses on the influence of biomass type, activation method, specific surface area, and resulting electrochemical performance, with the aim of providing direction for the development of highly competitive, sustainable, and effective activated carbon compounds for use in upcoming energy storage systems.

METHOD

This study applies a systematic integrative literature review, which combines systematic search methods with analytical synthesis to produce a comprehensive understanding of trends, gaps, and directions of supercapacitor development. This review aims to understand the latest developments in biomass-based activated carbon electrode materials and the key factors influencing supercapacitor performance.

Table 1. Research Method + Literature Selection & Classification.

Component	Description (with supporting references)
Research Design	Systematic Literature Review (SLR) following PRISMA 2020 to evaluate biomass-derived activated carbon for supercapacitors (Haider et al., 2025; Manimekala et al., 2025; Zhu et al., 2025).
Databases Used	Scopus, ScienceDirect, Google Scholar—common sources across related studies.
Search Keywords	“biomass activated carbon”, “chemical activation”, “porous carbon”, “supercapacitor performance”, “electrolyte” (Neme et al., 2022; Li et al., 2023; Behzadi Pour et al., 2024).
Inclusion Criteria	Biomass-derived activated carbon; activation using KOH, $ZnCl_2$, H_3PO_4, $CaCl_2$, molten salts; characterization data (BET, pore distribution, morphology); electrochemical metrics reported (Ahmed et al., 2018a, 2018b; Peng et al., 2016; Z. Pan et al., 2023)
Exclusion Criteria	Non-biomass carbon, no activation method, missing BET/capacitance data, incomplete electrochemical results (Muflihatun, 2025; Neme et al., 2022)
Biomass Types Used in Classification	Pea skin, carrot waste, rice husk, coconut shell, coffee grounds, pomelo mesocarp, bagasse, palm EFB, nettle leaves (Ahmed et al., 2018a,b; Ganesan et al., 2014; Peng et al., 2016; Yadav et al., 2023; Gillespie et al., 2025; Nguyen et al., 2025)

Activation Methods Used in Classification	KOH, $ZnCl_2$, H_3PO_4, $CaCl_2$, molten salt activation, CO_2 dual activation, nitrogenation via urea (Farma et al., 2013; Lu et al., 2016; Rustamaji et al., 2022)
Electrochemical Metrics for Classification	BET surface area, micro/mesopores, electrolytes (H_2SO_4, KOH, $LiClO_4$, EMIM-BF_4), specific capacitance (112–270 F/g) (Pal et al., 2019; Z. Pan et al., 2023); Chen et al., 2023; Mir et al., 2025)
Final Output of SLR	Synthesis of relationships among biomass → activation → porosity → electrolyte → supercapacitor performance, supported by >20 primary studies.

Despite extensive studies on biomass-derived activated carbon for supercapacitors, several gaps remain evident. First, the reviewed literature shows large variations in biomass type, activation methods, and testing conditions, yet no standardized comparative framework exists to systematically evaluate how specific biomass compositions influence pore structure and electrochemical performance (Ahmed et al., 2018a,b; Peng et al., 2016). Second, although multiple activation agents (KOH, $ZnCl_2$, H_3PO_4, $CaCl_2$, molten salts) have been explored, direct cross-comparison of activation efficiency—in terms of cost, energy consumption, porosity tuning, and stability—remains limited (Farma et al., 2013; Lu et al., 2016; Rustamaji et al., 2022). Third, studies often rely on a single electrolyte system, leaving insufficient understanding of pore–electrolyte compatibility, ion accessibility, and the influence of electrolyte composition on capacitance trends (Pal et al., 2019; Z. Pan et al., 2023); Chen et al., 2023). Fourth, inconsistencies in reported BET surface areas versus specific capacitance indicate that the field lacks a unified model linking pore architecture to electrochemical behavior (Ganesan et al., 2014; Z. Pan et al., 2023). Finally, most studies emphasize laboratory-scale synthesis and short-term cycling, revealing a major gap in scalability, long-term durability, and environmental assessment of biomass-activated carbon production (Dos Reis et al., 2020; Nguyen et al., 2025)

RESULT AND DISCUSSION

Activated Carbon Synthesis Method

The synthesis process of biomass-based activated carbon generally involves two main stages: carbonization and activation, where the carbonization temperature ranges from 400–800 °C in an inert atmosphere to produce a basic carbon structure. Different carbonization methods, such as pyrolysis and hydrothermal carbonization, allow specific control over porosity and surface area. Hydrothermal carbonization has been shown to increase the porosity and surface area of carbon materials, with characteristics that favor supercapacitor applications.

Activating Agents

Chemical activation agents can be broadly classified into four categories: alkaline (KOH, NaOH), acidic (H_2SO_4, H_3PO_4), oxidizing (H_2O_2, $KMnO_4$, K_2FeO_4), and salts (K_2CO_3, $FeCl_3$, $FeCl_2$, $KHCO_3$ and $ZnCl_2$) (Manimekala et al., 2025). KOH serves as an appropriate activating agent due to its environmental friendliness compared to other agents, and it effectively promotes favorable porosity with a narrow pore size distribution. chemical activation using agents like KOH, H_3PO_4, and $ZnCl_2$ is used to expand the porosity and increase the specific surface area of the material (Zhou et al., 2022). Commonly used biomass types include coconut shells, rice husks, coffee grounds, bamboo, corncobs, banana peels, and sawdust due to their abundant availability and high carbon content. The use of KOH activation agents generally results in a surface area of up to >2000 m^2/g with a uniform micropore distribution (Li et al., 2023). H_3PO_4 activation tends to form mesopores that accelerate the diffusion of electrolyte ions. $ZnCl_2$ activation produces activated carbon with a combination of micro-mesopores and high structural stability during the charging and discharging cycles (El-Nemr et al., 2023).

Type of Electrolyte

Advances in supercapacitor research indicate that electrolyte selection plays a critical role in determining the electrochemical performance, safety, and energy efficiency of the device. Aqueous electrolytes such as H_2SO_4, KOH, and Na_2SO_4 are widely used due to their high ionic conductivity and low cost, although their voltage window is limited to approximately

1 V (Mendhe & Panda, 2023). In contrast, organic electrolytes based on acetonitrile or propylene carbonate solvents with $LiPF_6$ or $TEABF_4$ salts can achieve a voltage window of up to 3 V, thereby increasing energy density, but have volatility and stability issues (Pal et al., 2019). Meanwhile, ionic liquids (ILs) such as EMIM-BF_4 or BMIM-PF_6 offer a wider potential window, high thermal stability, and resistance to evaporation, making them suitable for high-voltage applications despite their relatively low conductivity and high cost. Another innovation is solid electrolytes or polymer gels, which improve device safety and flexibility, but still require improvements in ionic conductivity (Behzadi Pour et al., 2024).

Furthermore, hybrid electrolytes combining aqueous–organic components or containing redox additives can expand the voltage window while improving specific capacitance and cycling stability (Mir et al., 2025). Recent research highlights electrolyte engineering approaches such as IL viscosity engineering, the addition of redox-active compounds, and the in-situ synthesis of polymer gels to improve supercapacitor efficiency and lifetime (S. Pan et al., 2020). Overall, the future direction of supercapacitor development focuses on creating stable, high-capacity electrolytes that are compatible with a variety of sustainable activated carbon-based electrode materials.

Biomass-based materials' specific capacitance ranges from 250 to 450 F/g, depending on the material type, surface area, and pore structure (Dos Reis et al., 2020). Surface modification through nitrogen doping has been shown to improve the electrical conductivity and electrochemical stability of activated carbon. Overall, the combination of high-carbon biomass materials, KOH-based activation, pore structure modification, and heteroatom doping provides significant performance improvements in supercapacitor applications.

Table 2. Overview of Biomass-Derived Activated Carbon for Supercapacitors

Sources	Activation Method	Surface area of activated carbon (m^2g^{-1})	Electrolyte	Specific capacitance (Fg^{-1})	References
Pomelo mesocarps	$CaCl_2$ + urea nitrogen-doped	974.6	2 M KOH	245 (0.5 A g^{-1})	(Peng et al., 2016)
Oil palm empty fruits bunch	KOH + CO_2	1704	1 M H_2SO_4	150 (10 mA cm^{-2})	(Farma et al., 2013)
N modified-coconut shell	$H_2SO_4/(NH_4)_2S_2O_4$	489.3	6 M KOH	179 (0.5 A g^{-1})	(Yang et al., 2018)
Rotten carrot	$ZnCl_2$	1154.99	1 M $LiClO_4$	142.7 (1 mA cm^2)	(Ahmed et al., 2018b)
Pea skin	$ZnCl_2$	1253.17	1 M H_2SO_4	192.7 (1 mA cm^2)	(Ahmed et al., 2018a)
Rice husk	H_3PO_4	1493	1 M H_2SO_4	112 (1A g^{-1})	(Ganesan et al., 2014)
Firewood	Na_2CO_3 + K_2CO_3	818	1 M H_2SO_4	189 (0.2 A g^{-1})	(Lu et al., 2016)
Nettle leaves	KOH	1951	EMIM BF4	163 (0.5 A g^{-1})	(W. Fan et al., 2019)
N modified-oil palm empty fruits bunch	$CaCl_2$	640.6	6 M KOH	176.7 (2 mV s^{-1}	(Rustamaji et al., 2022)
Sugar cane bagasse	$CaCl_2$	805.5	6 M KOH	270 (5 A g^{-1})	(J. Liu et al., 2016)

Based on the analysis of various literatures discussing the use of local biomass as a source of activated carbon for supercapacitor electrodes, it can be concluded that the type of biomass, activation method, and type of electrolyte used have a significant influence on the resulting electrochemical performance. The biomass activation process to produce activated carbon plays a critical role in determining the surface area, pore morphology, and electrochemical performance in supercapacitor applications. In general, chemical activation methods such as KOH, $ZnCl_2$, H_3PO_4, $CaCl_2$, and carbonate base mixtures have been shown to improve pore structure and charge storage performance (Muflihatun, 2025).

Activated carbon from pomelo mesocarps activated using a mixture of $CaCl_2$ and urea yielded a surface area of 974.6 m²/g and a specific capacitance of 245 F/g in a 2 M KOH electrolyte. These values demonstrate the positive effect of nitrogen doping on charge storage and ionic conductivity. Oil palm empty fruit bunch biomass activated using a combination of KOH and CO_2 gas achieved a high surface area of 1704 m²/g and a capacitance of 150 F/g in a H_2SO_4 electrolyte, demonstrating that dual activation is effective in producing a large microporous structure.

Nitrogen-modified coconut shell-based materials with $H_2SO_4/(NH_4)_2S_2O_4$ activator exhibited a surface area of 489.3 m²/g and a capacitance of 179 F/g in 6 M KOH electrolyte, indicating that the addition of nitrogen can improve cycle stability and electron conductivity. In rotten carrot biomass, activation with $ZnCl_2$ yielded a surface area of 1154.99 m²/g and a capacitance of 142.7 F/g in $LiClO_4$ electrolyte, confirming the effectiveness of $ZnCl_2$ in forming a structurally stable micro-mesoporous combination. The use of $ZnCl_2$-activated pea skin as the base material also exhibited a surface area of 1253.17 m²/g and a capacitance of 192.7 F/g in H_2SO_4, demonstrating the consistency of $ZnCl_2$ activation results in enhancing electrolyte ion diffusion. Rice husk activated carbon activated with H_3PO_4 has a high surface area (1493 m²/g) but exhibits a lower capacitance value of 112 F/g, indicating that the dominance of the mesoporous structure is less than optimal for rapid charge storage.

Firewood material activated using a mixture of Na_2CO_3 and K_2CO_3 produces a moderate surface area (818 m²/g) with a capacitance of 189 F/g, indicating that mild base activators remain effective in increasing pore area at a low cost. Nettle leaf biomass activated with KOH exhibits a very high surface area of 1951 m²/g with a capacitance of 163 F/g in EMIM BF_4 ionic electrolyte, indicating good suitability for high-voltage applications with strong thermal stability (Chen et al., 2023).

Furthermore, activated carbon from empty oil palm fruit bunches modified with nitrogen using $CaCl_2$ exhibited a surface area of 640.6 m²/g and a capacitance of 176.7 F/g at 6 M KOH, indicating the important role of nitrogen in improving electrochemical performance. In sugarcane bagasse biomass, $CaCl_2$ activation yielded a moderate surface area of 805.5 m²/g but the highest capacitance of 270 F/g, reflecting the contribution of mesopores to fast and efficient ion transport.

Overall, these comparisons indicate that KOH and $ZnCl_2$ activation yielded the highest surface area, while $CaCl_2$-based activation and nitrogen doping provided better electrochemical stability. Aqueous electrolytes such as H_2SO_4 and KOH provided high capacitance due to their high ionic conductivity, while ionic liquid-based electrolytes such as EMIM BF_4 were superior in terms of thermal stability and operating voltage range (Z. Pan et al., 2023).

CONCLUSION

Based on the results of the analysis of various literatures discussing the use of local biomass as a source of activated carbon for supercapacitor electrodes, it can be concluded that the kind of biomass, activation technique, and electrolyte employed all have a significant impact on the electrochemical performance of biomass-derived activated carbon, according to a thorough analysis of numerous experiments. Excellent capacitance and stability are achieved by combining high-carbon biomass precursors with chemical activation using KOH and $ZnCl_2$ to create activated carbon with high porosity and specific surface area. Moreover, conductivity and ion transport are greatly enhanced by the addition of heteroatom doping, such as nitrogen. While neutral electrolytes offer superior long-term cycle stability, alkaline-based systems particularly KOH produce the highest specific capacitance values among all electrolytes. In line with this novelty, this review identifies crucial future research directions, namely the need for comparative studies across biomass and activators with standardized protocols, evaluation of the performance of a single carbon material in various electrolytes, and development of predictive models linking synthesis parameters to electrochemical performance. Furthermore, studies on sustainability and industrialization opportunities are still very limited. Few studies have assessed the scalability, energy consumption of the activation process, production cost analysis, or environmental impact of various biomass-based carbon synthesis pathways. Furthermore, only a few studies have evaluated long-term stability (>10,000 cycles) under real-world application conditions, including high temperatures, extreme humidity, or varying current densities. This gap highlights the need for more holistic, application-oriented research. Therefore, this review not only summarizes recent developments but also provides a conceptual foundation and strategic research direction for the development of next-generation sustainable supercapacitors.

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