IPC
Indonesian Physics Communication
Department of Physics, Universitas Riau, Pekanbaru, Indonesia
p-ISSN 1412-2960 | e-ISSN 2579-521X
Vol. 22 | No. 3
November 2025
Web: https://kfi.ejournal.unri.ac.id
E-mail: kfi@ejournal.unri.ac.id

Biomass-derived activated carbon from acacia pods as a green electrode material for supercapacitors

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ABSTRACT

Biomass from acacia pods has great potential as a raw material for activated carbon due to its abundant availability, environmentally friendly nature, and high carbon content. In this study, acacia pods were processed into charcoal and then chemically activated using 1 M $ZnCl_2$ solution, followed by carbonization at 600°C and physical activation at 850°C to improve the quality of the carbon structure formed. Physical characterization showed that the synthesized activated carbon had a density of 58.8 g/cm^3, which plays an important role in the electrode formation and mechanical stability of the material. The electrochemical properties were evaluated using cyclic voltammetry (CV) in 3 M Na_2SO_4 electrolyte, which produced a nearly rectangular voltammetric curve, indicating good capacitive response and efficient ion movement within the electrode. The maximum specific capacitance obtained was 159 F/g at a scan rate of 1 mV/s, indicating promising charge storage capabilities. These results confirm that acacia pods can be converted into high-performance activated carbon, while offering a sustainable electrode material alternative for environmentally friendly supercapacitor applications.

Keywords: Acacia pods; activated carbon; electrode material; local biomass; supercapacitor

Received 03-10-2025 | Revised 18-11-2025 | Accepted 20-11-2025 | Published 30-11-2025

INTRODUCTION

In recent years, global awareness of the ecological crisis has increased, particularly driven by the increasing frequency of natural disasters. This has made environmental pollution a major global concern [1]. It cannot be denied that society's shift away from fossil fuels is driven by the urgent need for more reliable energy storage systems in both research and industry [2]. From an ecological perspective, renewable energy is increasingly receiving attention as a research focus due to the increasing global energy needs [3]. Although the production, distribution and conversion of energy from renewable energy sources, especially electricity, can take place optimally, the biggest obstacle still faced lies in the limited capacity for large-scale storage [4]. Recently, energy storage devices such as supercapacitors, Li-ion batteries, and fuel cells have received significant attention from researchers, driven by the rapid increase in global population and the energy crisis. Among these technologies, supercapacitors are considered one of the latest innovations in energy storage and conversion systems due to their superior characteristics, including high power density and long cycle life [5]. Supercapacitors are considered promising energy storage devices due to their high charging and discharging rates, long cycle life, and high power density. Their electrochemical performance is strongly influenced by the intrinsic properties of the electrode materials used. Therefore, the development and design of electrode materials with superior performance have become a major focus of research, with the aim of improving the efficiency, capacity, and durability of supercapacitor systems [6].

Biomass-based materials are currently considered suitable as supercapacitor electrodes due to their low cost, abundant availability, environmental friendliness, and sustainability. Another advantage is their relatively simple preparation process. After activation, activated carbon from biomass exhibits a larger specific surface area, along with heteroatoms such as N and O, which play a role in increasing the number of active sites in the carbon material. Various types of biomass have been utilized as electrode materials in supercapacitor development [7]. Furthermore, carbon-based supercapacitor electrodes are reported to be promising candidates due to their large surface area, high porosity, good electrical conductivity, and favorable surface function. These characteristics are the result of various efforts to develop activated carbon-based supercapacitor electrodes derived from biomass, which are considered more economical and sustainable in the long term [8]. Biomass is known as one of the largest carbon reservoirs. High-temperature carbonization processes are commonly used to produce carbon materials from biomass. However, due to the complex structure of biomass, the formation of a regular arrangement of carbon atoms is difficult to achieve through pyrolysis alone, so the resulting carbon is generally amorphous. This amorphous carbon has numerous defects in the form of pores that act as storage containers and transport pathways for electrolyte ions. Furthermore, amorphous carbon also contains heteroatoms, which are more easily wetted by electrolytes and contribute to the formation of pseudocapacitance [9].

Indonesia boasts abundant natural resources, supported by fertile soil and high biodiversity. Of the world's approximately 40,000 flora species, approximately 30,000 grow in Indonesia, including the acacia tree [10]. Acacia is a fast-growing tree species and is widely cultivated in plantations to meet the demand for wood fiber. The cutting cycle for acacia trees is set at 8 – 9 years, which is considered ecologically safe [11]. Acacia crassicarpa is a species of acacia tree cultivated in Indonesia and plays a vital role in supporting the fiber wood industry. Acacia wood has several advantages over other wood species, including high yield (51.46%), moderate lignin content (18 – 33%), good pulp and paper strength, and low alkali requirement (16%) [12]. These characteristics contribute to the formation of well-controlled doping in the final material, as reported in previous studies utilizing acacia pod-based carbon for various applications. In general, the constituent polymers consist of cellulose, hemicellulose, and lignin, and are supplemented with various polar and non-polar compounds. Lignocellulosic biomass itself is generally composed of major elements (C, H, O, N, K, and Ca), minor elements (Mg, Al, Si, P, Cl, Na, S, and Fe), and trace elements such as B, Mn, and Ti [13].

This research focuses on the use of acacia pods obtained from the forest area of PT. Riau Andalan Pulp & Paper, Pangkalan Kerinci, Pelalawan Regency, as a source of carbon material for supercapacitor technology. The potential of acacia pods is examined as an efficient, sustainable, and environmentally friendly electrode material. The conversion process was carried out by converting acacia pods into activated carbon through a new method that is simple, low-cost, and environmentally friendly, namely chemical activation using low concentrations of $ZnCl_2$ in a single-stage high-temperature pyrolysis with the integration of N_2 and CO_2 gases. Electrochemical characteristics, especially specific capacitance, were evaluated using cyclic voltammetry (CV) techniques. The results of this study are expected to confirm that acacia pods have the potential to be a high-quality carbon source for supercapacitor electrode materials that not only support the effectiveness and efficiency of renewable energy conversion systems but are also in line with efforts to maintain environmental sustainability.

RESEARCH METHODOLOGY

Materials

The source of carbon material used is Accasia pods obtained from acacia plantations in the forest area of PT. Riau Andalan Pulp & Paper, Pangkalan Kerinci, Pelalawan Regency, Indonesia. The initial stage of making activated carbon begins with sample preparation, namely acacia pods precarbonized for 2 hours at a temperature of 100°C – 250°C. Next, the precarbonized sample is crushed using a mortar and ground using a ball milling for ±20 hours. The results of the ball milling in the form of powder are sieved to obtain homogeneous particles measuring 60 µm. After being sieved, the acacia pod carbon will be activated physicochemically. Zinc chloride ($ZnCl_2$) and sodium sulfate (Na_2SO_4) are used to conduct this study. Distilled water is used for solution preparation and monolith neutralization.

Activated Carbon Preparation

Porous activated carbon from acacia pods was produced through a one-stage activation and pyrolysis method in a N_2/CO_2 gas atmosphere, which consists of carbonization and physical activation processes. Approximately 50 grams of acacia pod powder was impregnated with zinc chloride ($ZnCl_2$) using a powder to KOH ratio of 1.467:1. A total of 34.075 grams of KOH was dissolved in 250 ml of distilled water, then mixed with 50 grams of acacia pod powder using a hot plate. The mixture was stirred using a magnetic stirrer at 300 rpm for 2 hours, then dried in a vacuum oven for approximately 2 days. Once dry, the powder was compressed into a monolith or pellet form using a hydraulic press with a pressure of 8 tons. The carbonization process began at room temperature and increased slowly by 1°C per minute until it reached an initial temperature equivalent to 289°C, which was maintained for 1 hour. The temperature was then increased again by 3°C per minute until it reached the optimal carbonization temperature of 600°C. This was followed by physical activation using carbon dioxide (CO_2) gas up to a temperature of 850°C. At this stage, the temperature increase rate was 10°C per minute, and the sample was maintained for 3 hours. After that, the activated carbon was soaked in distilled water until it reached a neutral pH, and dried. Then the sample was polished to a thickness of 0.2 mm with a mass ranging from 0.01 – 0.02 grams before physical and electrochemical characterization was carried out.

Physical & Electrochemical Characterization

The characterization of carbon electrodes was carried out by reviewing their physical and electrochemical properties. Physical analysis included measuring the electrode density calculated using standard formulas based on mass, diameter, and volume. Meanwhile, electrochemical testing was carried out in a two-electrode system, using an eggshell membrane as a separator and a 3 M Na_2SO_4 liquid electrolyte at room temperature. Two polished carbon monolith samples served as electrodes. Both electrodes were placed on separate stainless steel circles, with the duck eggshell membrane serving as a separator. All components were then assembled in a sandwich layer. Electrochemical characterization was carried out using cyclic voltammetry (CV) techniques to evaluate electrode performance.

RESULTS AND DISCUSSION

Density Analysis

The initial step in analyzing the physical properties of carbon electrodes from acacia pods was density measurement. The density value was calculated based on the mass, diameter, and thickness of the carbon electrode pellets. The erosion process in the samples indicated a decrease in the electrode's mass and volume. The difference in density values before and after the carbonization and physical activation processes provides an indication of the changes in the material's characteristics [14]. The increase in furnace temperature affects the dimensions of the precursor monolith, triggering the onset of density degradation. High furnace temperatures, ranging from 30°C to 600°C in a nitrogen environment, allow the evaporation and decomposition of complex organic compounds. Water and volatiles completely evaporate at 150°C, followed by the release of hemicelluloses tightly bound in the lignocellulosic component. Cellulose, as a homopolysaccharide, decomposes significantly at temperatures between 300°C and 315°C, which breaks the D-glucose monomer chain and promotes the growth of carbon with a rich fibrous structure, as previously studied. Meanwhile, lignin, a complex amorphous polymer, decomposes at temperatures above 315°C [13]. Physical activation is performed at higher temperatures than carbonization to remove tar and ash. This step also increases pore size and forms more pores in the material, resulting in a decrease in electrode density [14]. As a result, the monolith sample experienced a decrease in density before and after the pyrolysis process at a temperature of 850°C as shown in Figure 1.

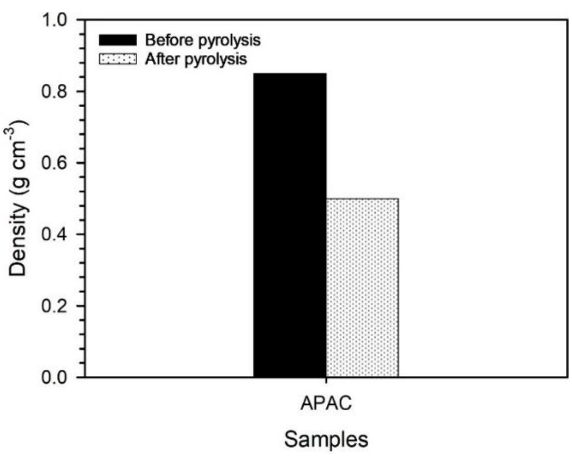

Figure 1. Precursor density before and after pyrolysis of acacia pods.

From the figure above, the sample shows a decrease in density after the one-stage integration process that occurs in carbonization and physical activation. In addition, the pyrolysis process gradually reduces the density of the APAC monolith from 0.85 g/cm3 and 0.50 g/cm3 which is equivalent to a decrease of 41.18%. This decrease in density is associated with the expansion of abundant pores, narrow pores, and larger pores on the surface of the APAC precursor. In addition, these features are very beneficial for improving the access of electrode interfaces in supercapacitor devices.

Electrochemical Analysis

The voltammetric curve shows the charging and discharging currents. The magnitude of the charge and discharge currents will increase if the electrode has a larger pore size. An increase in the positive charge current and the negative discharge current on the voltammetric curve indicates an increase in the capacitive properties of the electrode [15]. Characterization was performed at a low potential range of 0 – 1 V with a constant scan rate of 1 mV/s. The resulting CV curves show the relationship between current density and voltage, which produces a shape close to rectangular but not completely symmetrical [4]. The resulting curve is shown in Figure 2.

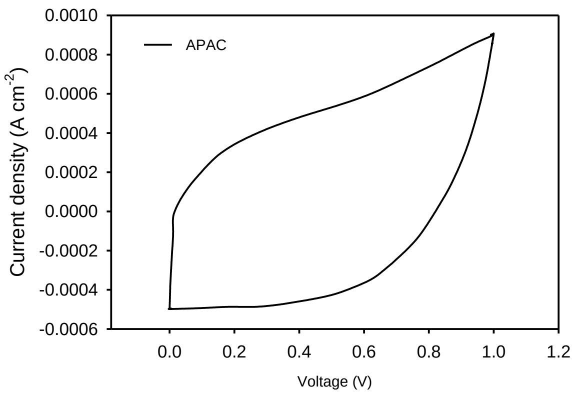

Figure 2. Cyclic voltammetry curve at a scan rate of 1 mV/s.

Figure 2 shows the CV measurement results that display a distorted rectangular-shaped curve, which is a typical characteristic of Electrical Double Layer Capacitor (EDLC) on biomass-based carbon electrodes. The specific capacitance value can be estimated from the area of the CV curve formed during the charging and discharging process, where the larger the area of the curve indicates the higher the specific capacitance produced [16]. The curve yields a specific capacitance of 159 F/g. Based on the specific capacitance data, we can determine the energy density and power density using standard equations. The maximum energy density and power density in this study were 22.17 Wh/kg and 79.91 W/kg, respectively.

CONCLUSION

This study has shown that acacia pods can be used as an environmentally friendly source of activated carbon for supercapacitor electrode applications. Through a chemical activation process using low-concentration $ZnCl_2$, followed by a carbonization stage at 600°C and physical activation at 850°C, a porous carbon material was obtained with a density decrease from 0.85 g/cm^3 before the process to 0.50 g/cm^3 after the process, equivalent to a decrease of 41.18%. The decrease in density is caused by the formation of abundant pores that function as electrolyte ion transport pathways as well as active areas for energy storage. Electrochemical characterization using cyclic voltammetry (CV) techniques in 3 M Na_2SO_4 electrolyte shows a nearly rectangular curve, which is a characteristic of Electrical Double Layer Capacitor (EDLC). A maximum specific capacitance of 159 F/g at a scan rate of 1 mV/s, with an energy density of 22.17 Wh/kg and a power density of 79.91 W/kg, was obtained, confirming the material's ability to store and transfer charges efficiently. Therefore, it can be concluded that acacia pods have the potential to be converted into high-performance activated carbon electrode materials that are economical, sustainable, and support the development of new, environmentally friendly renewable energy storage technologies.

ACKNOWLEDGMENTS

The research was financially supported by first-year Project of Fostered Village Program (PDB) at the Institute for Research and Community Service, the University of Riau with the title “An innovation in insecticides based on smoke-free waste combustion evaporation sediment as a sustainable solution for food security for farmers in Sumber Sari Village, Tapung Hulu District, Kampar Regency” contract No.: 29310/UN19.5.1.3/AL.04/2025.

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