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Preparation of Activated Carbon from Coffee Grounds as a Supercapacitor Electrode

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ABSTRACT

The growing demand for sustainable energy storage solutions has spurred interest in supercapacitors, with biomass-derived activated carbon emerging as a promising electrode material. This study investigates the fabrication and performance of activated carbon from spent coffee grounds for application in supercapacitors. Carbonization was carried out at 300°C, 500°C, and 700°C, followed by chemical activation using HCl, KOH, and $ZnCl_2$. The resulting activated carbons were characterized to determine their physicochemical properties. Optimal activated carbon was obtained at 700°C with KOH activation, yielding 84.75% fixed carbon and conforming to SNI 06-3730-1995 standards. Supercapacitor performance testing revealed that the best results were achieved using electrodes prepared from carbon obtained at 300°C and activated with $ZnCl_2$, yielding a voltage of 352.9 mV and a capacitance of 465.58 μF after a 1-minute charge. These findings suggest that spent coffee grounds are a viable source of electrode material for efficient, low-voltage supercapacitors.

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1. INTRODUCTION

Electricity has become a fundamental necessity for people worldwide, profoundly influencing nearly every sector of life. In Indonesia, one widely used technology across various industries is the supercapacitor, a device for energy storage. Supercapacitors have demonstrated remarkable performance as environmentally friendly energy storage systems due to their fast charging, high power density, long-term stability, low cost, and relatively easy production processes [1-3]. Supercapacitors represent an attractive energy strategy to reduce environmental pollution from fossil fuel exploitation and have found broad applications in electronics and transportation [4-7]. Compared to conventional batteries or capacitors, supercapacitors offer several advantages, including longer lifespan, simple design, rapid charging time, and, most importantly, safety. Their fast charging capabilities make them more promising than batteries [8]. Supercapacitors operate by storing charge through the movement of electrical current, though not all moving charges constitute electric current [9-10].

Activated carbon is commonly used as the active material for supercapacitor electrodes due to its low cost, abundance in nature, high surface area, high porosity, and good electrical conductivity. Activated carbon can store charge through physical adsorption and desorption of electrolyte ions on the electrode surface [11-12]. Furthermore, activated carbon electrodes are easily polarized, stable in different solutions (acidic, basic, and aprotic), and remain stable within a specific temperature range [13].

Activated carbon is the most widely used material for supercapacitor electrodes because it is readily available, inexpensive, and easier to prepare compared to other forms of carbon [14-17]. The large specific surface area of carbon materials allows for the creation of porous structures that facilitate the formation of an electric double layer on the electrode surface, enhancing the performance of the supercapacitor.

Coffee is one of the most popular beverages globally, including in Indonesia, where coffee consumption has been steadily increasing. Data from the International Coffee Organization (2020, 2021) show a rise in coffee consumption from 279,000 tons in 2016 to 300,000 tons in 2020. This increased consumption directly correlates with the amount of coffee grounds produced. A study by students from the University of Indonesia found that an average coffee shop produces around 10 kg of coffee grounds daily. Over a year, this amounts to approximately 3,650 kg or 3.65 tons per coffee shop [18-20].

In the production of activated carbon, chemical activation methods (using KOH, $ZnCl_2$, NaOH, H_3PO_4, and HNO_3) and physical activation methods (using steam, CO_2, and air) are commonly employed. The choice of activator greatly influences the quality of the activated carbon. Both chemical and physical activation processes aim to enhance the electrochemical performance of supercapacitor electrodes. Activation increases the pore structure, surface area, and chemical composition of activated carbon. A larger surface area allows for greater ion adsorption (both cations and anions), which increases the capacitance of electric double-layer capacitors (EDLCs). However, this increase is not linear due to other factors, such as the pore structure [21-23]. In this study, HCl, $ZnCl_2$, and KOH were used as dehydrating activators to achieve high-quality carbon with enhanced pore development.

2. METHODS

2.1. Preparation of Activated Carbon

The primary objective of this stage is to produce activated carbon with a larger surface area. The coffee grounds were chosen as the carbon precursor due to their relatively high carbon content [22-24]. The process began with washing the coffee grounds with distilled water, followed by filtering and drying under the sun for two days. After drying, 200 g of coffee grounds were subjected to carbonization in a furnace at temperatures of 300°C, 500°C, and 700°C for 2 hours. The carbonized coffee grounds were then cooled in a desiccator. This process was repeated three times with different carbonization temperatures. The resulting samples were prepared for the activation process.

2.2. Carbon Activation

This stage aims to enhance the surface area of the carbon. The chemical activation process involved soaking 15 g of carbonized coffee grounds from each temperature variation in 105 ml of activating solutions: HCl, KOH, and $ZnCl_2$ (1 M concentration) for 24 hours. The carbon to activator ratio was 1:7. After activation, the samples were washed with distilled water until the filtrate had a neutral pH (pH 6–7), as measured with universal pH paper. The samples were then filtered and dried in an oven at 110°C for 2 hours.

2.3. Supercapacitor Fabrication

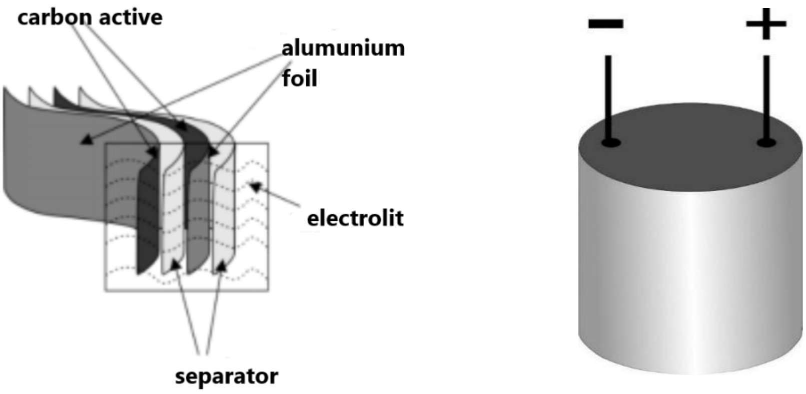
This step focuses on assembling the supercapacitor, which will later be tested for its electrical properties. The supercapacitor assembly consists of layers of mica plastic, aluminum foil, wires, activated carbon electrodes, separators, and an electrolyte. The electrolyte used was 1 M H_2SO_4, chosen for its small ion diameter, which facilitates easy penetration into the electrode pores.

Two activated carbon electrodes were weighed, and the materials—mica plastic, aluminum foil, and HVS paper—were cut into various sizes. The mica plastic was cut into 7.5 cm x 39 cm, and the HVS paper into sizes of 6.5 cm x 33 cm and 5 cm x 30 cm. The HVS paper was soaked in 1 M H_2SO_4 for 1 minute to enhance the purity of the activated carbon. The materials were then assembled into layers, forming a sandwich-like structure, with two layers of mica plastic and aluminum foil as the outer layers. A wire was attached to the aluminum foil to collect the charge. The activated carbon was then applied to the aluminum foil, and the separator (HVS paper soaked in electrolyte) was placed between the two layers of carbon. After assembling the layers, the stack was rolled into a cylindrical shape, and the ends were sealed with thick cardboard to prevent the electrolyte from drying out. The design of the supercapacitor is shown in Figures 1.

2.4. Supercapacitor Testing

This stage aims to evaluate the performance of the supercapacitor made from activated carbon derived from coffee grounds by measuring its electrical properties and determining the precision of the testing apparatus. The supercapacitor was charged by connecting both wires to a power source, using a 5V charger and a constant current of 1 A.

Voltage and capacitance measurements were taken for supercapacitors made with activated carbon at carbonization temperatures of 300°C, 500°C, and 700°C and activated with HCl, KOH, and $ZnCl_2$. Electrical properties were measured to establish the relationship between capacitance, voltage, and charging time [25]. A multimeter was used to measure voltage (V), and an LCR meter was used to measure capacitance (F). The charging time was varied from 0 to 3 minutes, with six repetitions for each supercapacitor sample. This process aimed to achieve good precision in the measurements. Precision was calculated by determining the %RSD (Relative Standard Deviation) or capacitance coefficient for supercapacitors with different carbonization temperatures and activators. Six iterations of data collection were performed for each sample, as required by [4].



(a) (b)

Figure 1. Design schematic of the inside (a) and outside (b) of the supercapacitor

3. RESULTS AND DISCUSSION

3.1. Carbon production

The results of carbon production using coffee grounds, also known as carbonization, were obtained by applying various carbonization temperatures: 300°C, 500°C, and 700°C. The carbonization outcomes are shown in Figure 2.

Figure 2. Coffee Ground Carbon Before Activation

The study on the production of activated carbon from coffee grounds involved two main processes: carbonization and activation, using different chemical activators—HCl, KOH, and $ZnCl_2$ at a concentration of 1 M. The results of the activation process using these various activators and carbonization temperatures are presented in Figures 3-5.

Figure 3. Activated Carbon at Carbonization Temperature of 300°C with HCl, KOH, and $ZnCl_2$ Activation

Figure 4. Activated Carbon at Carbonization Temperature of 400°C with HCl, KOH, and $ZnCl_2$ Activation

Figure 5. Activated Carbon at Carbonization Temperature of 500°C with HCl, KOH, and $ZnCl_2$ Activation

3.2. Supercapacitor Fabrication

The supercapacitor was successfully fabricated using activated carbon derived from coffee grounds as the electrode material. The result of the supercapacitor fabrication is shown in Figure 6.

Figure 6. supercapacitor based on activated carbon

3.3. Supercapacitor Performance Testing

The performance testing of the supercapacitor was successfully carried out. The test results yielded data on voltage and capacitance. Precision values were obtained after processing the capacitance data using Microsoft Excel. The voltage and capacitance values of the supercapacitor with various activators and carbonization temperatures are shown in Table 1.

Table 1. Shows the test results of the supercapacitor made with activated carbon using HCl, KOH and $ZnCl_2$ as the activating agent

Activating agent	Carbonization time (^oC)	Voltage (mV)	Capacitance (µF)
HCl	300	570,3	156.10
	500	323,4	68.78
	700	286,2	67.71
KOH	300	978,3	103.37
	500	498,2	65.54
	700	308,8	65.12
$ZnCl_2$	300	374	261,50
	500	467,9	84,21
	700	518,7	115,53

4. CONCLUSION

The preparation of activated carbon from coffee grounds has been successfully conducted. Activated carbon was produced by heating coffee grounds in a furnace at temperatures of 300°C, 500°C, and 700°C, followed by activation using HCl, KOH, and $ZnCl_2$ solutions. This activated carbon was then used as the base material for supercapacitor electrodes.

The carbonization temperature and activator type significantly influence the quality of the resulting activated carbon. As the carbonization temperature increased, the ash content increased, while the moisture and volatile content decreased. Most of the activated carbon samples met the quality standards for activated charcoal as per the SNI 06-3730-1995.

Supercapacitors were successfully fabricated using activated carbon from coffee grounds as the electrode material. The supercapacitor performance was tested by measuring voltage and capacitance. The results indicated that although the supercapacitors produced low voltage values, they exhibited relatively high capacitance. Voltage did not vary significantly with charging time. However, capacitance showed a decreasing trend after a charging time of 2 minutes. The capacitance precision of all supercapacitors met the Indonesian National Standard (SNI) requirement of no less than 95% (≥95%), and most of them met the International Standard (IS) with no less than 98% (≥98%).

DECLARATION

Author Contribution

P. A. Putra, processed the experimental data, performed the analysis, drafted the manuscript and designed the figure. Widayanti was involved in planning and supervised the work. All authors discussed the results and commented on the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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