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Effect of variations in current collectors types on the performance of supercapacitor cell carbon electrode from biomass stalk of curly chili

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ABSTRACT

A study on the fabrication of carbon electrodes from curly chili stem biomass processed through a dual approach involving both chemical and physical activation methods has been succesfully conducted. The chemical activation was performed with a 0.3 M solution $ZnCl_2$ at a temperature of 80°C with a stirring speed of 350 rpm, followed by physical activation at 900°C. The carbon electrode density was observed to decrease after the pyrolysis process. The electrochemical properties of the carbon electrodes were analyzed using cyclic voltammetry (CV) and Galvanostatic charge-discharge (GCD) methods, with a scan rate of 5 mV/s and a current density of 1 A/g. These tests were performed by varying the type of current collector, including SS 304, SS 316, and CANS. The CV and GCD analyses revealed that the SS 304 current collector provided the highest specific capacitance values, namely 56.91 F/g and 77.04 F/g, respectively. Based on the electrochemical analysis results, it is concluded that current collectors with type 304, demonstrate the best performance in carbon electrode applications for supercapacitors.

Keywords: Biomass; carbon electrode; curly chili stalk; current collector; supercapacitor

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INTRODUCTION

The shortage of global energy resources and environmental pollution, along with the increasing demand for portable electronic devices and electric vehicles in recent years, have made the development of renewable and sustainable energy storage systems critically impotent [1]. Researchers are currently developing and improving efficient energy storage devices, one of which is the supercapacitor [2]. A supercapacitor is an electrical energy storage medium that possesses high energy density and power density. It also has a high electrical capacitance [3].

Electrodes for supercapacitor applications are developed from various types of materials. Among them, activated carbon is widely utilized because it is inexpensive, simple to produce, highly pure, and possesses a large surface area, good porosity, environmental friendliness, and excellent electrochemical stability [4]. Activated carbon is derived from carbonaceous materials, is amorphous in structure, and can be produced from carbon-rich sources such as oil palm empty fruit bunches [5], young coconut fiber [6], rice husks [7], cocoa shells [8], and areca nuts [9].

Curly chili plants are one of the horticultural commodities widely cultivated in Indonesia. The leaves of curly chili plants range from 3 – 11 cm in length, and the stems can grow up to 50 – 100 cm. This plant has fibrous roots [10]. The stalk of the curly chili contains cellulose, hemicellulose, and lignin. Cellulose and lignin are the main components of plant cell walls, functioning as structural support and protection [11].

The current collector is a crucial component in supercapacitors that functions to conduct electrical current from the electrode to the external terminal of the device. It must possess excellent electrical conductivity to ensure that the internal resistance of the supercapacitor remains low, thereby maximizing the energy storage and power performance [12]. This study evaluated three types of current collectors i.e, stainless steel with a type of 304 (SS 304), stainless steel with a type of 316 (SS316), and used beverage cans (CANS) on the performance of a supercapacitor based on activated carbon derived from curly chili stalks (CCS). The results of this study show that the stainless steel current collector type 304 has the best performance, with specific capacitance values (C_{sp}) from CV and GCD tests of 56.91 F/g and 77.04 F/g, respectively.

MATERIALS AND METHODS

Materials

The curly chili stalks were obtained from traditional market waste at Panam regency, Pekanbaru. The chemical activating agent zinc chloride ($ZnCl_2$) with a concentration of 0.3M and the electrolyte sulfuric acid (H2SO4) with a concentration of 1M Smart-Lab brand. The Whatman No. 42 filter paper was selected and used as the separator material in the supercapacitor assembly with three types of current collectors (SS 304, SS 316, and CANS).

Methods

The biomass from curly chili stalks was first cleaned to remove any remaining broken chili pieces. Once cleaned, the biomass was sun-dried for 5 to 7 days until the sample mass reached a constant weight. The dried biomass was then subjected to a pre-carbonization process. A total of 30 grams of the sample was placed into a pre-carbonization tube and heated in an oven at 200°C for 2 hours. Afterward, the sample was ground using a mortar and pestle, then sieved with a 53µm (250 mesh) screen to obtain fine particles. Chemical activation was subsequently performed by blending 30 grams of carbon powder with $ZnCl_2$ 0.3 M and 150 mL of distilled water. The resulting activated carbon was then molded into coin-shaped pellets using a hydraulic press. The carbonization was conducted in a nitrogen (N_2) atmosphere at a temperature of 600°C, followed by physical activation using carbon dioxide (CO_2) gas at 900°C for 2 hours and 30 minutes. The use of current collectors in supercapacitors is very important because they serve as the medium for conducting electric current from the electrode to the external terminal of the device. Current collectors must have excellent electrical conductivity to keep the internal resistance of the supercapacitor low, thereby optimizing energy storage and power performance. In this study, the current collectors employed are stainless steel types 304 (SS 304) and 316 (SS 316), and recycled beverage cans (CANS).

CHARACTERIZATION

Density

Density measurement was conducted as part of the physical characterization of the supercapacitor electrode, aiming to evaluate the material structure, thermal stability, and the degree of carbon compaction achieved after the carbonization and activation processes. This parameter is essential to assess the efficiency of pore structure and material density in supporting the electrochemical performance of the carbon-based supercapacitor electrode. Density can be calculated using the following Equation (1):

$$\rho = \frac{m}{v} \tag{1}$$

where, m (g) is the mass, and v (cm^3) is the volume of the sample.

Electrochemical Analysis

The electrochemical behavior of the carbon electrode was evaluated cyclic voltammetry (CV) at a scan rate of 1, 2, 5, and 10 mV/s and galvanostatic charge-discharge (GCD) measurements at a current density of 1, 2, 5, and 10A/g with a voltage of 1 V. This electrochemical analysis utilized three types of current collector (SS 304, SS 316, and CANS) and 1 M H_2SO_4 as the electrolyte. The specific capacitance (C_{sp}) derived from the CV and GCD data can be determined using Equations:

$$C_{sp}, CV = \frac{(I_c - I_d)}{s \ x \ m} \quad (2)$$

$$C_{sp}, GCD = \frac{2 \ I. \Delta t}{m. \Delta V} \quad (3)$$

where, I (A) is the current, Ic (A) is the charging current, Id (A) is the discharging current, s denotes scan rate, m stands for the mass, Δt (s) indicates the discharge time, and ΔV (V) refers the potential window.

In addition, the galvanostatic charge–discharge (GCD) method can also be used to determine the specific energy (E_{sp}) and specific power (P_{sp}) of the carbon electrode for the supercapacitor. E_{sp} and P_{sp} can be calculated using the following equations:

$$E_{sp} = \frac{C_{sp} \ x \ \Delta V^2}{7.2} \quad (4)$$

$$P_{sp} = \frac{3600 \ x \ E_{sp}}{\Delta t} \quad (5)$$

where, V represents the potential (V), C_{sp} denotes the specific capacitance (F/g), Δt is the time interval (s), and E stands for the energy (Wh).

RESULTS AND DISCUSSION

Density

Density analysis is the first stage in the physical characterization of carbon-based electrode materials and plays a key role in revealing their structural and physical characteristics. Density, which denotes the mass contained within a unit volume, reflects the material's compactness and is determined by dividing its mass by its volume. This parameter offers essential information regarding how densely the carbon particles are packed, which can significantly affect the material's porosity, mechanical stability, and overall electrochemical behavior. Generally, a higher density implies a more tightly packed structure with reduced porosity, while a lower density suggests a more open or porous structure that may facilitate better ion diffusion during electrochemical processes. The value of density increases proportionally with sample mass, provided the volume remains unchanged, and conversely, it decreases when the volume increases while mass remains constant. For this reason, precise density measurements are critical in the development and optimization of carbon electrodes, especially for energy storage devices such as supercapacitors, where structural efficiency greatly influences performance [8].

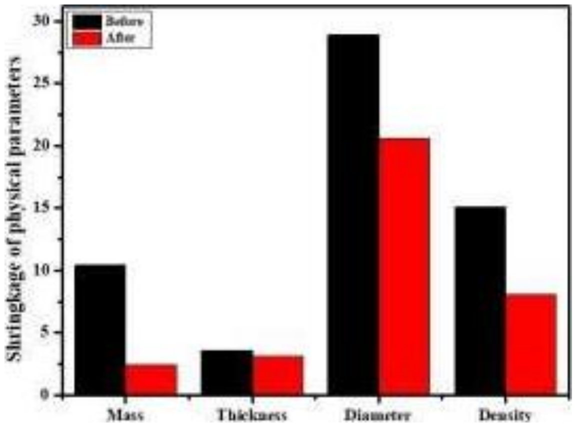


Figure 1. Electrode density before and after pyrolysis process.

The reduction in physical parameters such as mass, diameter, thickness, volume, and pellet density after the carbonization process is a result of thermal decomposition of volatile compounds. During this process, functional groups containing oxygen and hydrogen elements, along with non-carbon components and impurities, undergo degradation and are released as gases. The elimination of these volatile compounds leads to the restructuring of the carbon matrix and promotes pore formation, resulting in a more stable and porous carbon framework.

Electrochemical Analysis

Figure 2 presents the graph of the CV curve of the CCS sample in 1 M H_2SO_4. The curve obtained from the cyclic voltammetry (CV) method typically exhibits a hysteresis or rectangular shape, where a wider curve indicates a higher specific capacitance. The current versus potential curve produced in this method is referred to as a voltammogram [13]. The value of the specific capacitance for each sample is determined based on the charging current (I_c) and discharging current (I_d) obtained at a scan rate of 5 mV/s. The CV measurement results show that the SS 304 current collector has a higher specific capacitance value compared to the other current collectors, with a value of 56.91 F/g. The SS 316 current collector has a specific capacitance of 49.74 F/g, and the current collector made from a CANS has a value of 47.76 F/g with a scan rate of 5 mV/s.

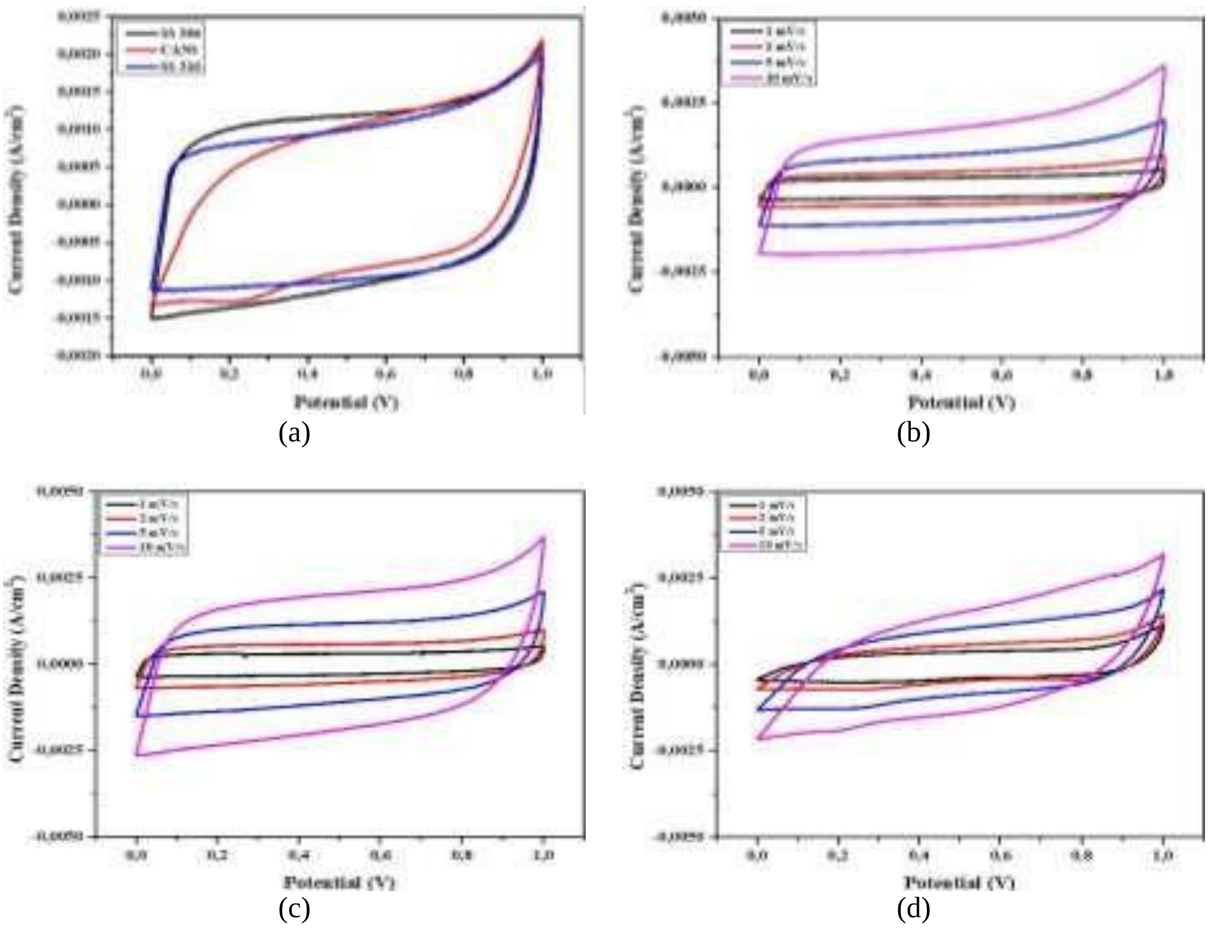
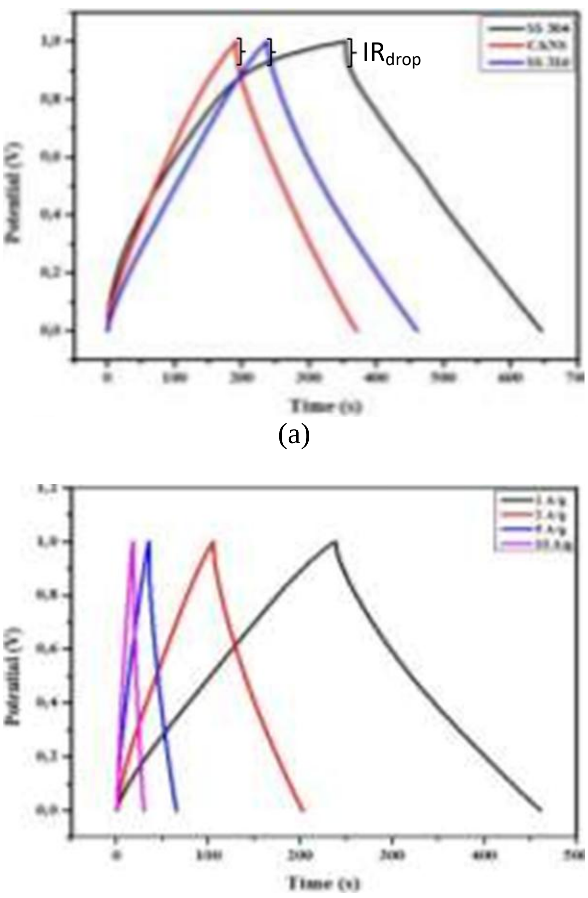


Figure 2. CV curve of (a), various current collectors, (b) SS 316, (c) SS 304, (d) CANS at various scan rates.

Figure 3 shows the GCD curves of the three variations of current collectors. The voltage versus time curves exhibit a linear pattern with a positive slope during charging and a negative slope during discharging. Deviations from linearity may occur due to the increase in voltage over time, influenced by constant internal resistance, which leads to a sharp voltage drop during the transition from the charging to the discharging process [14]. The GCD measurement results show that the SS 304 current collector exhibits a higher specific capacitance value compared to the other current collectors, with a value of 77.04 F/g. The SS 316 current collector recorded a specific capacitance of 57.33 F/g, while the CANS current collector yielded 47.84 F/g with a current density of 1 A/g.

In Figure 3 (a) and Table 1 with a current density of 1 A/g, there is an internal voltage drop (IR_{drop}) at the beginning of the discharge process of the GCD test result curve. IR drop is a voltage drop that occurs when electric current passes through the internal resistance of a source such as a battery or cell. This voltage drop causes the voltage available at the source terminal to be lower than the no-load voltage. Internal resistance is affected by various factors, including the type of material, temperature, and construction [15].



(a) (b)

(c) (d)

Figure 3. GCD curve of (a), various current collectors, (b) SS 304, (c) SS 316 (d) CANS at various current densities.

Table 1. Calculation results of E_{sp}, P_{sp}, and IR_{drop} values with a current density of 1 A/g.

Current collector	C_{sp} (F/g)	IR_{drop} (Ω)	E_{sp} (Wh/Kg)	P_{sp} (W/kg)
SS 304	77.04	0.07	6.64	134.40
SS 316	57.33	0.059	7.96	132.83
CANS	47.84	0.034	10.70	129.13

CONCLUSION

In summary, carbon activated electrodes were successfully synthesized from curly chili stalk biomass by using physics chemical activation. This study aimed to assess how different current collector materials impact the electrochemical performance of the produced carbon electrodes. Among the tested current collectors, the stainless steel with a thickness specification of 304 mm (SS 304) demonstrated the most superior performance. The specific capacitance (C_{sp}) values obtained were 56.91 F/g from CV analysis and 77.04 F/g from GCD analysis. These findings indicate that the choice of current collector plays a critical role in determining the efficiency of the electrode. In particular, the thinner current collector, Stainless Steel 304, provided better electrical conductivity and reduced resistance, which in turn enhanced the overall capacitance performance. These results indicate that a stainless steel 304 current collector can enhance the energy storage capability of carbon electrodes. Therefore, stainless steel 304 is regarded as the best candidate for developing high-performance supercapacitors using carbon materials derived from biomass.

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