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Properties of Active Carbon Derived from Arabica Coffee Pulp and Parchment using Hard Template Method

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ABSTRACT

Utilization of coffee residues such as pulp and parchment into activated carbon provides an alternative approach to electrodes in supercapacitors. The hard template method is used because of its ability to produce a more regular pore structure and higher surface area, which is very important for supercapacitor applications. This research aims to study the effect of template and activation temperature on the characteristics of coffee pulp and parchment using the hard template method. The synthesis process involves carbonization, templating with silica, and activation under nitrogen atmosphere at different temperatures. The resulting materials were characterized to evaluate their structural, surface, and electrochemical properties. The results obtained that higher activation temperature enhances surface area and electrochemical performance, indicating the potential of coffee-based activated carbon as an electrode material for supercapacitors

Keyword: *Supercapacitor, Activated Carbon, Coffee Pulp, Coffee Parchment, Hard Template, Activation.*

ABSTRAK

Pemanfaatan limbah kopi seperti kulit dan sekam kopi menjadi karbon aktif yang memberikan pendekatan alternatif untuk elektroda pada superkapasitor. Metode hard template digunakan karena kemampuannya menghasilkan struktur pori yang lebih teratur dan luas permukaan lebih tinggi, yang sangat penting untuk aplikasi superkapasitor. Penelitian ini bertujuan untuk mempelajari pengaruh jenis template dan suhu aktivasi terhadap karakteristik kulit dan sekam kopi dengan menggunakan metode *hard template*. Proses sintesis melibatkan karbonisasi, pembentukan template dengan silika, dan aktivasi dalam atmosfer nitrogen pada berbagai suhu. Material yang dihasilkan kemudian dikarakterisasi untuk mengevaluasi sifat struktural, permukaan, dan elektrokimianya. Hasil penelitian menunjukkan bahwa kenaikan suhu aktivasi meningkatkan luas permukaan dan kinerja elektrokimia, yang mengindikasikan potensi karbon aktif berbasis kopi sebagai material elektroda untuk superkapasitor.

Kata kunci: Superkapasitor, Karbon Aktif, Kulit Kopi, Sekam Kopi, *Hard Template*, Aktivasi.

1. Introduction

Limited energy sources and energy loss during use are issues that are often encountered in everyday life. In addition, energy consumption in the technology and industrial sectors is increasing every year, making energy efficiency an increasingly important consideration. The increasing consumption of non-renewable fossil fuels and the high price of fossil fuels have raised concerns about their rapid depletion, as well as their adverse environmental impacts such as greenhouse gas emissions and air and soil pollution. Therefore, it is important to develop environmentally friendly energy generation and storage technologies, with a focus on energy storage devices such as supercapacitors and batteries that have received increasing attention in recent research [1].

Supercapacitors are energy storage devices that are being intensively developed by researchers. Compared to conventional capacitors, supercapacitors offer a number of advantages, including high specific capacitance (more than 100 F/g), long lifetime, and extremely fast charge and discharge times of seconds. Supercapacitors have a high specific power of between 5 and 20 kW/kg, making them highly efficient devices for energy storage. The materials used in the manufacture of supercapacitors consist of two main components, namely electrodes and electrolytes, with activated carbon being the main choice in the manufacture of electrodes due to its advantages such as large specific surface area, ease of manufacture, and good porosity [2].

The widespread use of activated carbon in supercapacitors poses challenges related to the increasing demand for activated carbon raw materials which often come from expensive and non-renewable sources, such as wood, coal, and petroleum residues. Therefore, it is necessary to find alternative raw materials that are more renewable, readily available, and less costly. Biomass, as a source of activated carbon feedstock, is emerging as a promising solution, with various studies showing that biomass waste such as coffee peels, coffee parchments, bamboo, and palm kernel shells have the potential to be used as activated carbon feedstock [3].

In Indonesia, particularly in Aceh, coffee production in 2022 reached 75.3 thousand tons, generating a large amount of waste, especially coffee pulps and parchments. This coffee waste is often disposed of carelessly, potentially causing environmental problems due to the content of toxic organic compounds such as caffeine and polyphenols. However, coffee pulps and parchments contain high levels of cellulose, hemicellulose, and lignin, which have the potential to be utilized as raw materials for making activated carbon. The utilization of coffee waste will not only reduce environmental impact but can also support the development of supercapacitors made from activated carbon. Previous research has examined the effect of activator concentration on the characteristics of supercapacitor materials made from coffee pulp, but the results show uneven pore distribution [4].

However, most existing studies still focus on chemical activation and rarely evaluate structural regularity at the nanoscale, resulting in limited control over pore uniformity and ion transport behavior. Recent international studies [26] highlight that achieving ordered pore architecture is critical for improving capacitance and rate capability in carbon-based supercapacitors, yet no work has systematically applied the hard template method specifically to coffee pulp and parchment waste. This unresolved limitation forms a clear research gap that this study addresses by employing a hard template route to improve structural ordering and electrochemical performance. Therefore, this study aims to utilize the hard template method in the preparation of activated carbon from coffee waste to produce supercapacitors with more regular pore characteristics and better performance.

2. Method

2.1 Material

Arabica coffee pulp and parchment were collected from the coffee agroindustry in Bener Meriah, Aceh Province, Indonesia. Solvent-based silica nanoparticle dispersion, hydrofluoric acid (HF), and liquefied petroleum gas (LPG) were used as received without further purification. All reagents were of analytical grade.

2.2 Preparation of Activated Carbon

The preparation of activated carbon from coffee waste was conducted through several main stages, namely washing, drying, carbonization, activation, and template removal. Coffee pulp and parchment were thoroughly washed with tap water and soaked to remove surface impurities, followed by sun drying for approximately three days. The dried samples were carbonized in a pilot-scale pyrolysis reactor at 400˚C for 60 minutes to produce biochar. The resulting biochar was then mixed with a colloidal silica dispersion at a mass ratio of 1:2 (biochar:silica) and stirred for 2 hours at room temperature. The mixture was activated at 600˚C and 700˚C for 60 minutes in a furnace under an inert atmosphere. Subsequently, the silica template was removed using 10 wt% hydrofluoric acid (HF) solution for 1 hour, and the obtained product was washed with distilled water until

neutral pH (~7) and dried at 110˚C to yield the final activated carbon powder. A schematic flowchart summarizing the experimental procedure is presented in Figure 1.

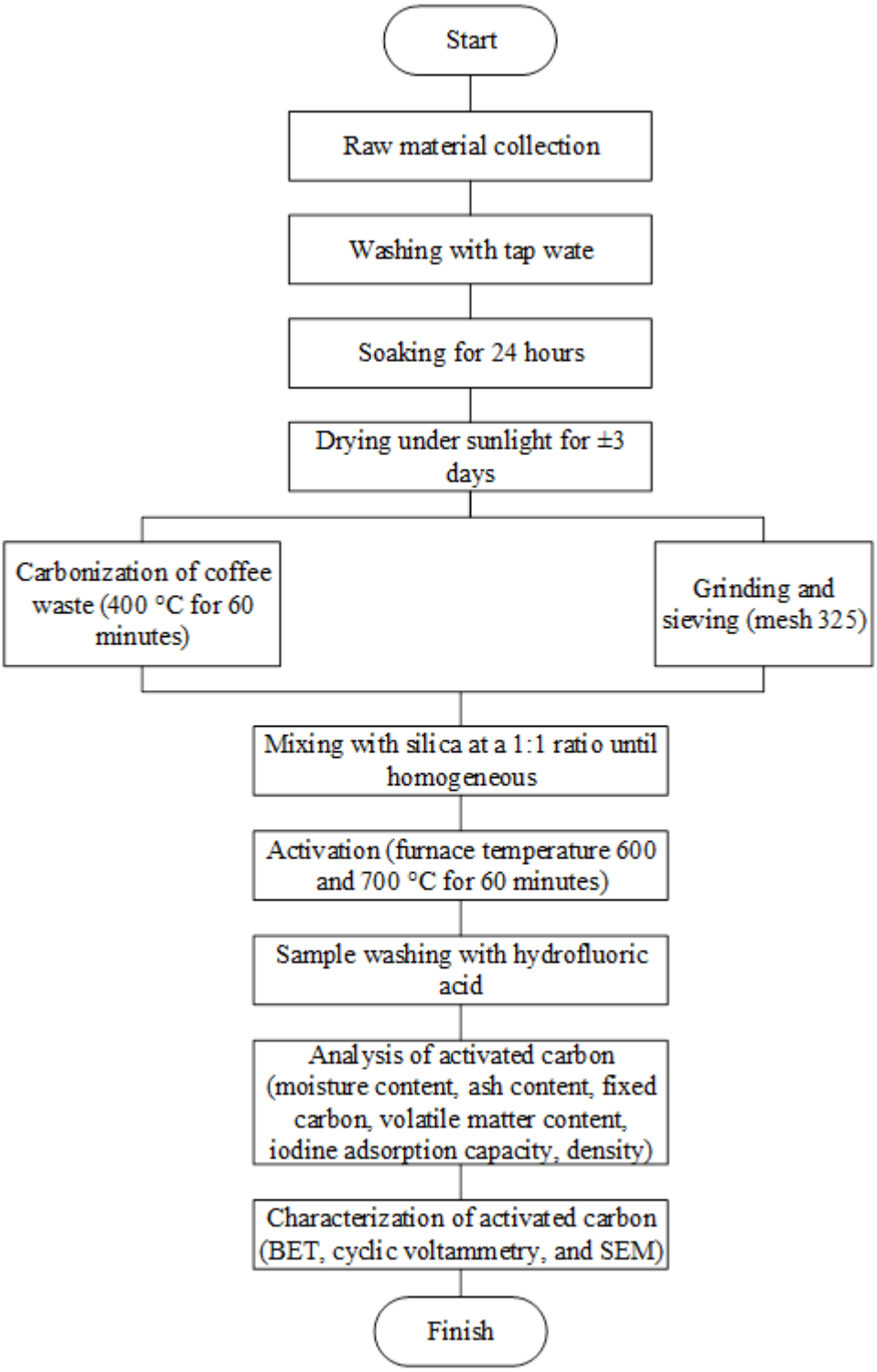

Figure 1. Flowchart Process

2.3 Characterization

The activated carbon samples were analyzed using several characterization techniques, including proximate analysis, iodine adsorption, density measurement, Brunauer–Emmett–Teller (BET) surface area analysis, cyclic voltammetry (CV), and Scanning Electron Microscopy (SEM) to evaluate their physical and electrochemical properties. The naming and coding of the coffee waste–based activated carbon samples (pulp and parchment) are presented in Table 1.

Table 1. Coffee waste activated carbon samples (pulp and parchment)

Sample Name	Sample Symbol
Coffee pulp with activation temperature of 600˚C	KK 6
Coffee pulp with activation temperature of 700˚C	KK 7
Coffee parchment with activation temperature of 600˚C	SK 6
Coffee parchment with activation temperature of 700˚C	SK 7

3. Result and Discussion

3.1 Proximate Analysis

Proximate analysis aims to determine whether the activated carbon that has been synthesized from coffee waste (pulp and parchment) has met the quality requirements of standard activated carbon which refers to SNI 06-3730-1995. Proximate analysis of activated carbon from coffee pulp and parchment waste can be seen in Table 2.

Table 2. Proximate Analysis of Coffee Waste Activated Carbon (Pulp And Parchment)

No	Sample Name	Water Content (%)	Ash Content (%)	Volatile Matter Content (%)	Fixed Carbon Content (%)
1	KK 6	3.38 ± 0.16	6.28 ± 0,09	24.61 ± 0.73	65.72 ± 0.49
2	KK 7	3.59 ± 0.36	6.69 ± 0,24	20.30 ± 1.96	69.40 ± 2.24
3	SK 6	4.70 ± 0.09	5.65 ± 0,41	21.90 ± 0.34	67.73 ± 0.76
4	SK 7	4.96 ± 0.25	5.74 ± 0,53	21.08 ± 0.79	68.21 ± 0.51

Water content is calculated to determine the hygroscopic properties of coffee waste activated carbon (pulp and parchment). Where hygroscopic properties are the ability of activated carbon to absorb water vapor from the air. The lower the moisture content, the less water is left behind and covers the activated carbon pores. The larger the pores, the more the surface area of activated carbon increases. The resulting relatively small water content value indicates the water content contained in activated carbon has evaporated in the carbonization and activation process [5].

Table 1 shows that the water content of the activated carbon samples ranges from 3.38 ± 0.16% to 4.96 ± 0.25%, indicating that the majority of moisture was successfully removed during the carbonization and activation processes. All samples meet the SNI 06-3730-1995 quality standard for powder activated carbon (≤ 15%), demonstrating that the produced activated carbon has excellent thermal dehydration characteristics. When the effect of activation temperature is examined, samples activated at 600˚C (KK6: 3.38 ± 0.16%; SK6: 4.70 ± 0.09%) show slightly lower moisture content than those activated at 700˚C (KK7: 3.59 ± 0.36%; SK7: 4.96 ± 0.25%). However, the differences between these temperature groups are small compared with their standard deviations. Because the SD values overlap between 600˚C and 700˚C samples, the variation is considered not statistically significant, indicating that activation temperature does not produce a meaningful change in moisture retention.

From an error analysis perspective, all SD values remain low (SD < 0.40%), indicating good consistency and repeatability of the measurement method. The relatively higher moisture content in parchment-based samples (SK6 and SK7) may be attributed to their higher cellulose content, which increases water-binding capacity compared with pulp. This trend is consistent with previous findings reported by [6], where activation temperature also showed minimal influence on moisture content in biomass-based activated carbon. Overall, the results confirm that the carbonization and activation stages effectively reduced residual moisture. In addition, both coffee pulp and parchment demonstrate strong potential as high-quality precursors for activated carbon production.

Ash content is the amount of oxide content (ash). Ash content is the amount of metal oxide content consisting of minerals in a material that cannot evaporate in the process of ignition. The ash content of activated carbon will affect the quality of activated charcoal, where if the ash content is high, there will be a blockage in the activated charcoal so that the surface area is reduced [7].

Ash content represents the inorganic residue remaining after combustion and is influenced by the mineral composition of the precursor as well as the thermal treatment process. In this study, ash content values are expressed as mean ± standard deviation (SD) to reflect measurement variability and support error analysis. Table 1 show that ash content ranges from 5.65 ± 0.41% to 6.69 ± 0.24%, with the highest value observed in coffee parchment activated at 700˚C (6.69 ± 0.24%) and the lowest in parchment activated at 600˚C (5.65 ±

0.41%). All samples meet the SNI 06-3730-1995 standard for powdered activated carbon (≤ 10%), indicating that the thermal treatment successfully reduced non-carbon inorganic components.

Although there is a tendency for ash content to increase at higher activation temperatures, the differences are relatively small compared with their respective standard deviations. The SD overlap between samples activated at 600˚C and 700˚C suggests that the variation is not statistically significant, meaning that the change in temperature does not meaningfully influence the inorganic residue content. This observation is in line with the fact that ash formation is more strongly governed by the inherent mineral composition of the raw biomass rather than activation temperature alone.

The slight increase in ash content at 700˚C may be associated with limited secondary oxidation during cooling, where exposure to air can promote partial combustion of carbon, leaving behind more ash residues [8]. The higher ash content in pulp-based activated carbon compared with parchment is attributed to the higher mineral and inorganic compound content naturally present in coffee pulp, which results in more ash after thermal decomposition. A similar trend was also reported in previous studies [9] involving activated carbon derived from Nipa Palm Fronds, where biomass with higher mineral content produced greater ash residues.

Volatile matter testing aims to determine the content of compounds that can evaporate at 950˚C. On heating above 900˚C nitrogen and sulfur will evaporate, and these components are called volatile matter. High levels of volatile matter are caused by the presence of non-carbon atoms attached to the surface of activated carbon, especially H atoms and O atoms. These non-carbon atoms are strongly bound to C atoms on the surface of activated carbon in the form of compounds of CO_2, CO, CH_4 dan H. These non-carbon atoms are an impurity that covers the pores of activated carbon thus reducing its effectiveness in absorbing adsorbates [6].

Volatile matter indicates the fraction of thermally unstable components released during heating, and its value reflects the completeness of thermal decomposition during carbonization and activation. In this study, volatile matter content is presented as mean ± standard deviation (SD) to evaluate both measurement variability and the reliability of the results. Table 1 shows that the volatile matter content ranges from 20.30 ± 1.96% to 24.61 ± 0.73%, with the highest value observed in coffee pulp activated at 600˚C (24.61 ± 0.73%) and the lowest in pulp activated at 700˚C (20.30 ± 1.96%). All samples fall within the SNI 06-3730-1995 standard requirement for powdered activated carbon (≤ 25%), indicating that the thermal process used was sufficient to decompose most volatile compounds.

A general decreasing trend is observed when activation temperature increases from 600˚C to 700˚C. However, the degree of reduction varies across samples, and the differences must be interpreted in relation to the SD values. For instance, the relatively large SD in sample KK7 (±1.96%) suggests that variability within measurements is comparable to the difference between temperature treatments, indicating that the decrease in volatile matter is not statistically strong. Conversely, SK6 and SK7 show smaller SD values, suggesting more stable measurements, although the overall reduction remains moderate.

The decline in volatile matter at higher temperatures aligns with established principles of biomass pyrolysis, where elevated activation temperatures promote more complete decomposition of non-carbon compounds and release of volatile organic components [10]. Meanwhile, the slightly higher volatile matter content in pulp-based activated carbon at 600˚C is attributed to its higher initial content of thermally labile organic compounds compared with parchment, resulting in greater release of volatiles during heating.

Fixed carbon content is the fraction of carbon contained in charcoal in the form of solids/carbon left after the determination of moisture, ash and fly content. Analysis of bound carbon content is carried out to determine the level of purity of carbon from charcoal, so that the value of fixed carbon content can be known as the potential for activated carbon. Perfect carbonization causes the resulting carbon to have a higher carbon content. The amount of bound carbon content in the resulting activated carbon is influenced by ash content and volatile substance content [11].

Table 1 shows that the highest value of fixed carbon content in coffee pulps with an activation temperature of 700˚C is 69.40%, while the lowest value of fixed carbon content is obtained in coffee pulps with an activation temperature of 600˚C at 65.72%. The results of the analysis of fixed carbon content in this study have met the quality standards of activated carbon based on SNI 06-3730-1995, which requires a minimum fixed carbon content of 65% for powder-shaped activated carbon. Based on these results, the quality of coffee waste–based activated carbon (pulp and parchment) produced in this study can be categorized as good.

The data of the analysis of fixed carbon content shows that coffee waste activated carbon samples (pulp and parchment) with variations in activation temperature produce fluctuating fixed carbon values and tend to decrease at an activation temperature of 600˚C. The decrease in fixed carbon at 600˚C indicates that this temperature is not sufficient to optimize pore formation; as a result, part of the fixed carbon may degrade into gaseous or other volatile compounds, leading to lower fixed carbon content. Similar findings were also reported in [12] for activated carbon derived from tea grounds.

From a supercapacitor application perspective, fixed carbon content plays an important role because higher fixed carbon values generally correlate with better thermal stability, structural integrity, and improved carbon framework formation during activation. These characteristics contribute to the development of a more stable porous network, which is essential for enhancing charge storage capability and improving long-term cycling performance. Therefore, the increase in fixed carbon content at 700˚C in this study indicates a more favorable structure for potential application as an electrode material in supercapacitors.

3.2 Iodine Absorbency Analysis

Determination of the absorption capacity of activated carbon to iodine absorption aims to determine the absorption capacity of activated carbon to small molecules. The absorption capacity of activated carbon to iodine has a correlation to the surface area of activated carbon. The greater the value of iodine absorption obtained, it indicates the quality of the activated carbon produced will be better in absorption [7]. Graph of iodine absorption test results of coffee waste activated carbon (pulp and parchment) can be seen in Figure 2.

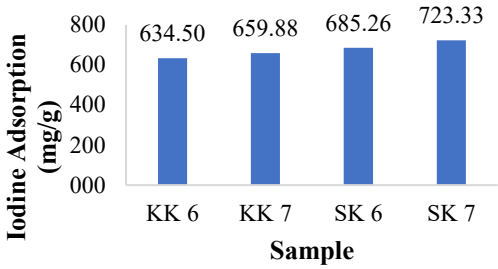

Figure 2. Graph of Iodine Absorption Test Results of Coffee Waste Activated Carbon (Pulp and Parchment)

Figure 2 shows that the highest iodine uptake value was obtained in coffee parchment with activation temperature of 700˚C at 723.33 mg/g, while the lowest iodine uptake value was obtained in coffee parchment with activation temperature of 600˚C at 634.5 mg/g. The results of the iodine absorption analysis in this study have not met the quality standards of activated carbon based on SNI 06-3730-1995, which is at least 750 mg/g for powder-shaped activated carbon, this is because there are still activated carbon pores that are covered by ash and not all activated carbon pores are open optimally exceeding the size of the I2 molecule so that the absorption capacity has not been maximized [13].

These results show that the higher the activation temperature used, the iodine absorption capacity increases. This is in accordance with research [14] which states that high temperatures are able to multiply pores and expand the surface of activated carbon, so that more iodine is absorbed. The iodine absorption value of coffee parchment is higher when compared to coffee pulp, this indicates that coffee parchment as raw material is more effective in producing activated carbon with larger surface area and better pore structure. The results obtained in this study were 723.33 mg/g lower when compared to the results obtained by [15] which is 761.4 mg/g.

3.3 Density

Density is one of the physical properties that affect the performance of supercapacitor cells. Density affects the specific capacitance value of supercapacitors. The smaller the density value, the more pores are produced so that the porosity produced will be greater. Density can determine the ability of supercapacitor cells as charge storage, the higher the density of the supercapacitor electrode, the smaller its ability to store charge [16]. The graph of the density test results of coffee waste activated carbon (pulp and parchment) can be seen in Figure 3.

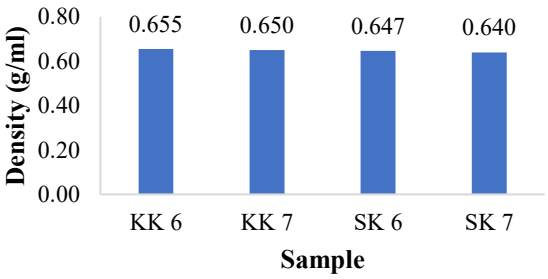

Figure 3. Graph of Density Test Results of Coffee Waste Activated Carbon (Pulp and Parchment)

Figure 3 shows that the highest density value was obtained in coffee parchment with activation temperature of 600˚C at 0.655 g/ml, while the lowest density value was obtained in coffee parchment with activation temperature of 700˚C at 0.640 g/ml. The results of density analysis in this study do not meet the quality standards of activated carbon based on SNI 06-3730-1995, which is a maximum of 0.30 - 0.35 g/ml for powder-shaped activated carbon. Based on the data obtained, the quality of coffee waste activated carbon (pulp and parchment) produced in this study is not good.

The density analysis graph data shows that the effect of activation temperature variation does not have a significant impact on the density value produced. The decrease in density value indicates that higher activation temperatures can open more pores so that the resulting density value is low. The results in this study are similar to the values obtained in research [17] conducted on activated carbon from onion pulp waste.

3.4 Surface Morphology Analysis

Morphological analysis on coffee waste activated carbon (pulp and parchment) was carried out on samples of coffee pulp and parchment with an activation temperature of 700˚C which was tested based on the highest iodine absorption value using SEM morphology instrument. The research samples analyzed were KK 7 shown in Figure 3 (a) and SK 7 samples shown in Figure 4 (b) at 2000x magnification as follows.

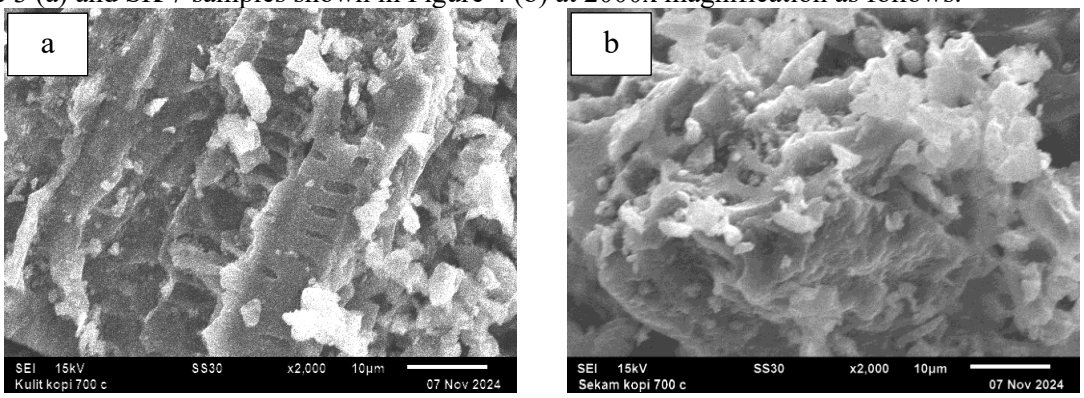

Figure 4. Results of SEM Morphological Analysis of Activated Carbon (a) Coffee Pulp, and (b) Coffee Parchment

Figure 4 shows that the pore structure of coffee waste activated carbon (pulp and parchment) is different. Figure 4 (a) shows a rough surface shape and the cavity is not evenly distributed and the pore surface is still covered by impurities. Figure 4 (b) shows a relatively small pore size.

Cavities in activated carbon produced by the hard template method using silica as a template material are formed from the removal of silica after the activation process. Template treatment using silica as a template is able to absorb organic compounds resulting in the formation of pores on the carbon surface. In addition, the pore cavity is formed due to the influence during the carbonization process, causing the decomposition of the lignocellulose structure [25]. Similarly, [16] reported that the shape of SEM morphology is influenced by the nature of the biomass material and other treatments used in the production of activated carbon.

3.5 Surface Area Analysis

N_2 gas adsorption-desorption analysis for coffee waste activated carbon (pulp and parchment) was analyzed using BET/SAA (surface area analyzer) measurements. In this BET method test, the sample analyzed was a powder sample with a sample mass of 0.1388 g. In principle, the surface area analyzer only determines how many adsorption points we want to measure (expressed in P/Po values) and then the tool will measure how much nitrogen gas is absorbed at each P/Po point entered previously, then the data will be expressed in an adsorption isotherm graph.

Surface area is the area occupied by a molecule of adsorbate/solute substance which is a direct function of the surface area of the sample. Thus it can be said that the surface area is the number of pores in each unit area of the sample. While the specific surface area is the surface area per gram [18]. The BET linear plot graph of coffee waste activated carbon (pulp and parchment) can be seen in Figure 5.

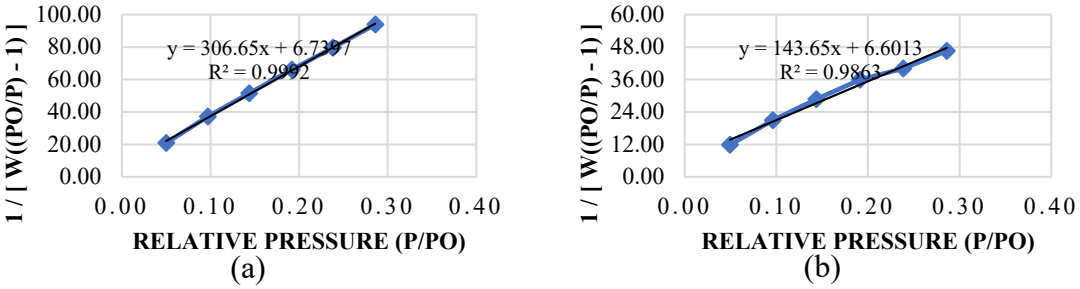

Figure 5. BET Linear Plot Graph of Coffee Waste Activated Carbon (a) Pulp and (b) Parchment

The samples used in this study for the BET method are samples with the highest iodine absorption values, namely KK 7 and SK 7 in the form of powder that has been activated as much as 0.1388 g with a degassing process for 80 minutes at a temperature of 300˚C to remove gas contamination in the activated carbon pores so that the resulting analysis results are more [19].

Based on Figure 5 (a) the graph obtained is 6 points with the regression equation y = 306.65x + 6.7397 with R^2 = 0.9992. The surface area of coffee pulp activated carbon obtained is 11.112 m^2/g. The results in this study are close to the value obtained by [20] with a surface area of 15.312 m^2/g conducted on activated carbon from teak leaf waste. While in Figure 5 (b) the graph obtained 6 points with the regression equation y = 143.65x + 6.6013 with R^2 = 0.9863. The surface area of coffee parchment activated carbon obtained is 23.178 m^2/g. The results in this study have also been obtained [21] with a surface area of 23,235 m^2/g conducted on activated carbon from coconut shell charcoal.

The surface area values obtained by coffee waste activated carbon (pulp and parchment) are 11,112 m^2/g and 23,178 m^2/g. This is in accordance with the value of iodine absorption where the parchment shows higher absorption (723.33 mg/g) compared to coffee pulp (659.88 mg/g). The difference in higher surface area values on activated carbon produced from coffee parchments compared to coffee pulp is influenced by differences in chemical composition, morphological structure, and the influence of silica as a template. The surface area values obtained from the surface area analysis of coffee waste activated carbon (pulp and parchment) can be seen in Table 3.

Table 3. Surface Area Values Obtained from Surface Area Analysis of Coffee Waste Activated Carbon (Pulp and Parchment)

Sample	Slope	Intercept	Correlation coefficient	C constant	Surface Area
KK	306.652 1/g	6.740 1/g	0.9992	46.499	11.112 m^2/g
SK	143.649 1/g	6.601 1/g	0.9863	22.761	23.178 m^2/g

3.6 Capacitance Analysis

Cyclic voltammetry is one of the most widely used techniques in measuring the electrochemical properties of activated carbon electrodes. Specific capacitance is the ability of an electrode to store charge at a certain voltage per unit mass of the electrode. The results of measuring the capacitance value of supercapacitors using the cyclic voltammetry method with a scan rate variation of 1 mV/s, 50 mV/s and 100 mV/s. In general, the resulting graph has the same shape in each variation. The greater the current generated, the greater the specific capacitance value [22]. From the measurement results, it is found that the largest capacitance value is in the measurement with a scan rate of 1 mV/s. The voltammogram curve of coffee waste activated carbon (pulp and parchment) can be seen in Figure 6.

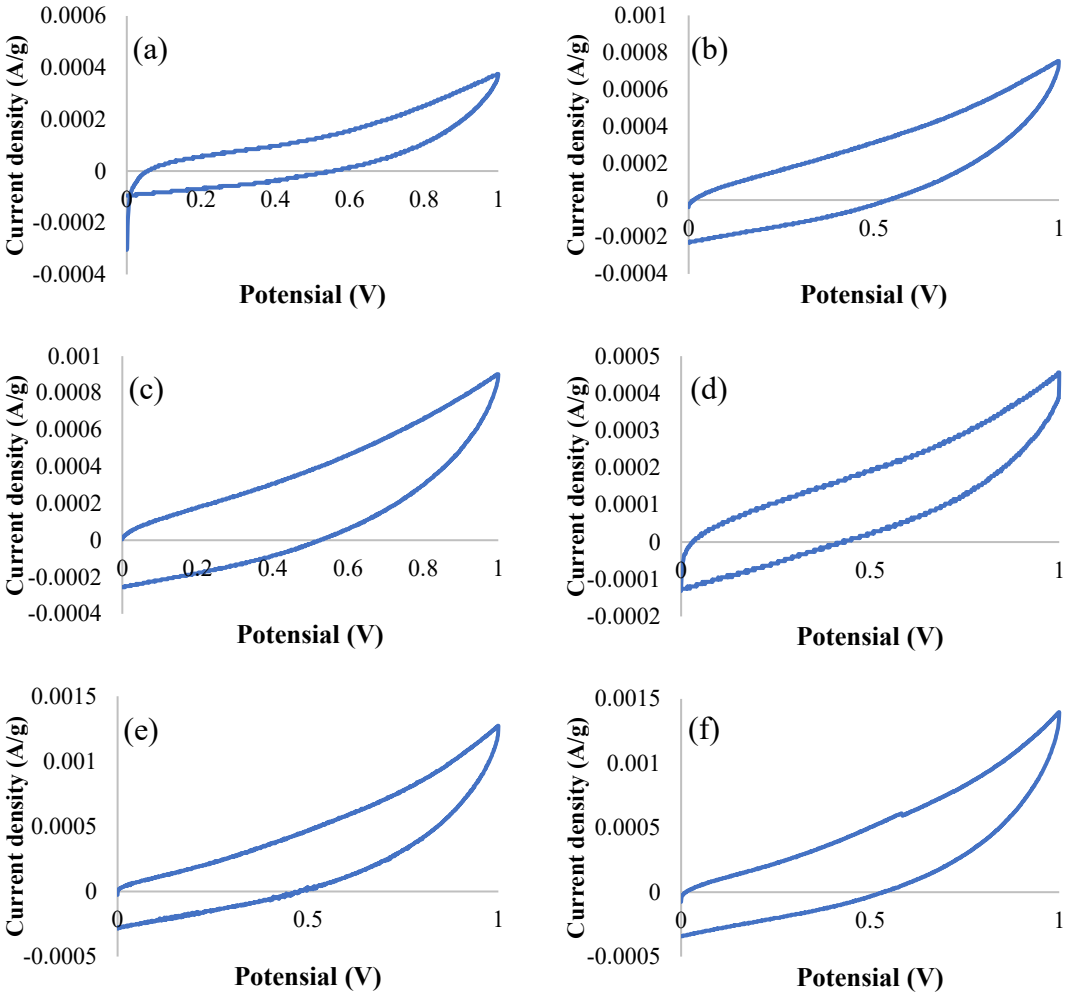

Figure 6. Voltammogram curves of coffee parchment activated carbon with scan rate of (a) 1 mV/s, (b) 50 mV/s, (c) 100 mV/s and coffee parchment with scan rate of 1 mV/s (d) 1 mV/s, (e) 50 mV/s, (f) 100 mV/s

Figure 6 shows the voltammogram curve of coffee waste activated carbon (pulp and parchment) which shows the area between the charge current (Ic) and discharge current (Id) which indicates the value of the capacitance produced by carbon electrodes at a scan rate of 1 - 100 mV/s with a potential range of 0 - 1 V which produces almost the same hysteresis curve shape. The highest capacitance values obtained on coffee waste (pulp and parchment) at an activation temperature of 600˚C with a scan rate of 1 mV/s were 6.81 and 8.35 F/g, at a scan rate of 50 mV/s the capacitance values were 0.34 and 0.44 F/g, while the lowest capacitance values were obtained at a scan rate of 100 mV/s which were 0.20 and 0.26 F/g. The capacitance value produced by coffee waste activated carbon on the pulp shows a significant decrease in capacitance value, while the parchment shows a slightly higher capacitance value at each scan rate than the coffee pulp. This indicates that the coffee parchment has a more optimized pore structure than the coffee pulp, which allows for better charge storage capacity.

When compared with the study by Kim et al. [23] on activated carbon paper electrodes prepared from rice husk-isolated cellulose fibers, which reported a significantly higher specific capacitance, the capacitance value obtained in this study is relatively low. This is because the carbonization process at 600 °C applied to coffee waste (pulp and parchment) has not been sufficient to significantly increase the surface area and porosity of the resulting activated carbon.The capacitance value of coffee waste activated carbon (pulp and parchment) can be seen in Table 4.

Table 4. Capacitance Value of Coffee Waste Activated Carbon (Pulp and Parchment)

Sample name	Weight (gr)	Scan rate (mV/s)	Potential range (V)	Capacitance value (F/g)
KK 6	0.02	1	1	6.81
	0.02	50	1	0.34
	0.02	100	1	0.20

Sample name	Weight (gr)	Scan rate (mV/s)	Potential range (V)	Capacitance value (F/g)
SK 6	0.02	1	1	8.35
	0.02	50	1	0.44
	0.02	100	1	0.26

Table 4 is the capacitance value obtained from cyclic voltammetry measurements which shows the greater the scan rate, the capacitance value will decrease. This happens because the scan rate affects the ions from the electrolyte into the coffee waste activated carbon electrode (pulp and parchment). A high scan rate indicates a fast voltage flow rate, as a result the time required for electrolyte ions to diffuse into the activated carbon is getting shorter. While the low scan rate results in a slow voltage flow rate so that the time required for ions to diffuse into the activated carbon is getting longer [24].

In addition, the trend of decreasing capacitance at higher scan rates is consistent with the general behavior of porous carbon electrodes reported in international studies, where limited ion diffusion at fast potential sweep conditions reduces the effective charge storage within micropores. This behavior has also been described by Simon and Gogotsi (2008), who emphasized that the ion transport limitation at high scan rates is a common challenge in carbon-based supercapacitor materials, especially when the pore structure is not yet fully optimized for rapid electrolyte access. Therefore, the capacitance characteristics obtained in this study align with established literature and highlight the need for improved pore development to enhance performance at higher operating rates [25].

4. Conclusion

This study demonstrates that variations in activation temperature have a limited influence on the proximate composition, density, and iodine adsorption of coffee waste–derived activated carbon. Although the volatile matter content decreases slightly with increasing temperature, other parameters such as ash, moisture, and fixed carbon contents remain relatively stable. The highest performance was observed in samples SK7 and KK7, which exhibited optimal density, iodine uptake, and surface morphology. More importantly, these findings reveal that activation temperature alone is not the dominant factor controlling pore development and electrochemical performance. Instead, the interaction between silica template type, concentration, and activation conditions plays a more decisive role. This insight highlights a new direction for optimizing biomass-derived carbon electrodes. In broader terms, the use of coffee waste as a precursor provides a sustainable and low-cost alternative for supercapacitor electrode materials, contributing to circular economy practices and the reduction of agricultural waste. Future work should explore different silica types and concentrations to further enhance pore uniformity and capacitance performance.

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