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Preparation of Activated Carbon from the Tree Leaves for Supercapacitor as Application

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Abstract
The increasing need for efficient and environmentally friendly energy storage solutions has prompted the investigation of sustainable materials for supercapacitor electrodes. This research examines the production of activated carbon from cocoa leaves by chemical and physical activation methods. The procedure includes pre-carbonization, chemical activation with potassium hydroxide (KOH), and physical activation in a carbon dioxide environment. The activated carbon produced has exceptional electrochemical performance, with a specific capacitance of 210 F/g at a current density of 1 A/g, an energy density of 29.7 Wh/kg, and a power density of 39.9 W/kg. These attributes underscore its viability as an economical, high-efficiency material for energy storage applications. Comparisons with previously examined biomass-derived electrodes further illustrate the advantages of activated carbon obtained from cocoa leaves regarding capacitance and energy storage. This study advances the development of sustainable energy storage technology, consistent with worldwide initiatives for renewable energy solutions.
Keywords: Activated carbon, supercapacitors electrode, biomass derived carbon, cocoa leaves

1. Introduction

Energy is essential in daily living. In the future, the production of energy using adequate and sustainable techniques will be a significant problem. Presently, more than 75% of societal energy consumption is derived from fossil fuels, such as coal, natural gas, and oil, all of which are non-renewable resources. Consequently, renewable energy must consistently replace fossil fuels prior to their depletion. Overreliance on fossil fuels contributes to global warming. It emits deleterious gasses straight into the environment [1][2]. Supercapacitors are electrochemical devices characterized by their exceptional rapid charging capability, elevated power density, lightweight construction, safe operation, and extended lifespan [3][4][5]. Supercapacitors are categorized into symmetric and asymmetric types [6][7]. Electrochemical double-layer capacitors (EDLC) and pseudo capacitors are categorized as symmetric supercapacitors, whilst hybrid capacitors are classed as asymmetric supercapacitors. The charge storing mechanism delineates the functionality of the supercapacitor. The EDLC stores energy electrostatically, while pseudo capacitors store energy by electrochemical redox or faradaic processes. The supercapacitor has four primary components: electrolyte, electrode, current collector, and separator. The performance of a supercapacitor mostly depends on the electrode material. The principal sources of energy production are coal, gas, oil, electricity, biomass, and heat generating. Activated carbon may be synthesized from biomass using thermal processes, either by direct carbonization or by first turning the biomass into biochar and then transforming the biochar into activated carbon [8]. Activated carbon is typically manufactured by chemical or physical activation techniques. The physical activation approach involves conducting the operation in an inert environment, where pyrolysis of carbonaceous material occurs at elevated temperatures to remove the majority of hydrogen and oxygen content [9]. The chemical activation technique involves carbonization at a low temperature range of 400–700 °C with a chemical activation agent [10]. Biomass or wood waste is often used to

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manufacture activated carbon using the chemical activation process [11]. Figure 1 depict the use of activated carbon in various application as shown below.

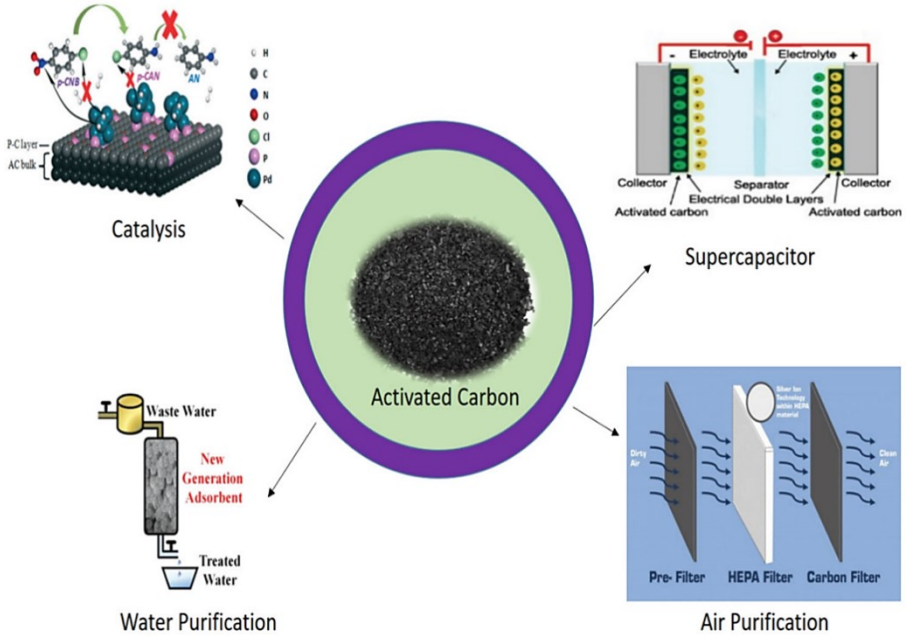

Figure 1. Use of activated carbon in various application [12]

Diverse activation agents have varying influences on the thermal decomposition of organic molecules in biomass. Numerous activation agents, including H_3PO_4, $ZnCl_2$, $FeCl_3$, KOH, H_2SO_4, and others, have been used in the synthesis of activated carbon [13]. Among them, H_3PO_4 is used most often. The H3PO4 activating agent enhances the surface area of activated carbon and augments the quantity of flaws at the anchoring sites for metal particles [14]. H_3PO_4 oxidizes carbon particles at temperatures between 500 and 600 °C to generate micropores [15] and has the benefit of preventing particle shrinking at a low operational cost.

Nuclear power, hydropower, and geothermal energy are fundamentally important for energy production. In the USA, energy production is consistently rising, however in Asia, there is variability in energy output. In 1990, global energy consumption was 8,795 million tonnes of oil equivalent (Mtoe), increasing to 14,080 Mtoe in 2017. Over the last two decades, there has been a significant transformation in energy generation. Post-2000, there has been a notable transformation in energy production and use. This results from global industrialization, technological innovation, and fast economic growth in both developed and emerging countries, including the United States, the European Union, China, Japan, and India. China, India, and Japan, three Asian nations, are projected to need future energy consumption of 3105 Mtoe, 934 Mtoe, and 429 Mtoe, respectively. In 2021, global energy production reached 14,736 Mtoe, whilst total energy consumption amounted to 13,865 Mtoe, reflecting a decline attributed to the effects of COVID-19. During COVID-19, lockdown measures and transit limitations were implemented. However, this year, the demand is projected to rise by 4.6% in 2022.

To address this difficulty, they need cost-effective, high-performance, eco-friendly electrical energy storage devices. Consequently, scientific and industrial research in this domain has focused considerable emphasis on emerging energy storage technologies, including supercapacitors and supercapacitor batteries. These energy devices possess several uses, ranging from portable electronics (such as mobile phones, compact digital cameras, PCs, and laptops) to hybrid electric vehicles and biomedical applications. Electrical energy storage systems should possess a mechanism that demonstrates longevity, elevated peak power, and energy density, assessed in relation to weight, volume, and cost.

This work presents cocoa leaves as a unique biomass source for the synthesis of activated carbon. It highlights the potential of cocoa leaves as a material for supercapacitor electrodes that is both cost-

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effective and ecologically sustainable. The study demonstrates improved electrochemical properties by employing an effective combination of chemical and physical activation processes. This research not only gives useful insights into the function that biomass precursors play in the development of energy storage technologies, but it also provides a methodical approach to the synthesis of high-performance activated carbon.

1.1 Supercapacitors

In this context, supercapacitors are crucial for energy and power storage owing to their greater energy density compared to capacitors, prolonged lifespan, rapid charging capabilities, higher power density than batteries, and broad operational temperature range. The supercapacitor, created in 1970 and sometimes referred to as an ultra-capacitor or electrochemical capacitor, operates on the same fundamental principles as normal capacitors. The specific surface area of the electrode and the thin electrolytic dielectric layer reduce the electrode separation distance, resulting in increased capacitance compared to traditional capacitors [16-18]. The most potential applications of supercapacitors are in automobiles, electrical gadgets, memory backup systems, and industrial equipment because to their distinctive properties. Supercapacitors exhibit power densities approximately tenfold greater (5–50 kW kg^{-1}) and substantially extended cycle lives (>10^4 cycles), albeit with lower energy densities (3–40 Wh kg^{-1}) compared to lithium-ion batteries. They are advantageous for alternating current (AC) ripple filtering, hybrid electric vehicles, and addressing peak power requirements in electrical grid storage [19-21]. Supercapacitors include a porous separator positioned between two identical electrodes and submerged in a liquid electrolyte. They primarily store charge by rapid electrostatic adsorption of electrolyte ions onto the surfaces of the oppositely charged electrodes, as seen in Figure 2.

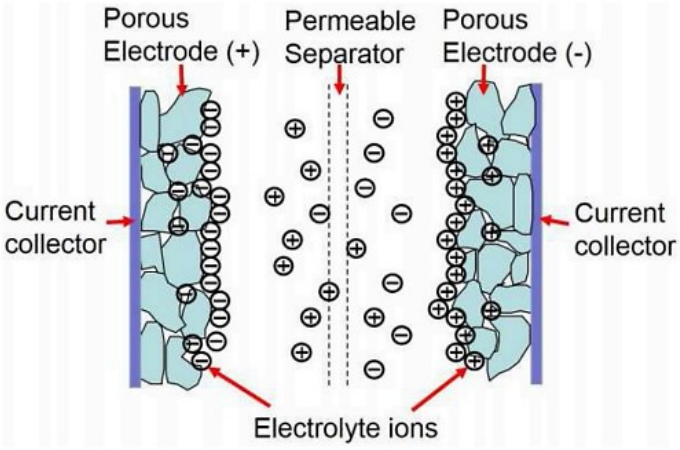

Figure 2. Schematic diagram of Capacitor as the charged state [22].

Supercapacitors allowed voltage determined by the permittivity in the double layers. Supercapacitors are available with organic, aqueous and ionic liquid electrolytes. The comparison of Li-ion battery with supercapacitors and capacitors presented in Table 1. A typical Ragon plot is shown in Figure 3.

Table 1. Compare among energy density, power density, efficiency, cyclability and durability of supercapacitor, capacitor and battery [23]

Feature	Battery	Supercapacitor	Capacitor
Recharge Cycle Lifetime	<10^3 sets	>10^6 sets	>10^5
Voltage	3.7V-4.2V	0V-2.7V	6-800
Self-Discharge Time	5%	30%	-
Energy Density (Wh/kg)	Max (20-150)	Min (0.8-10)	<0.1
Power Density (Wh/kg)	Min (50-300)	Max (500-400)	>10,000
Fastest Charging Time	Hours	Seconds ~ Minutes	10^{-3} - 10^{-6}
Fastest Discharging Time	0.3 ~ 3 Hours	< A few minutes	10^{-3} - 10^{-6}

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Charging	Complex	Simple	Simple

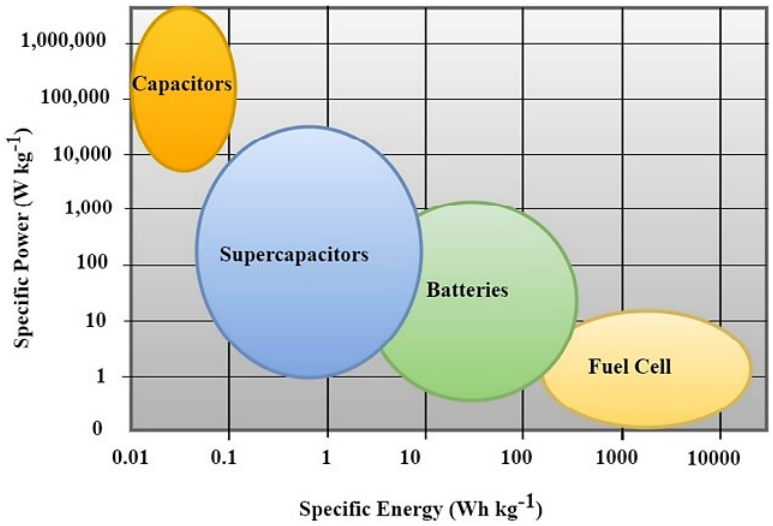

Figure 3. A Ragone plot comparing the energy and power of several electrochemical storage methods.

As the supercapacitor is emerging technology, it has come out with the major revolution in energy storage as shown in Figure 4.

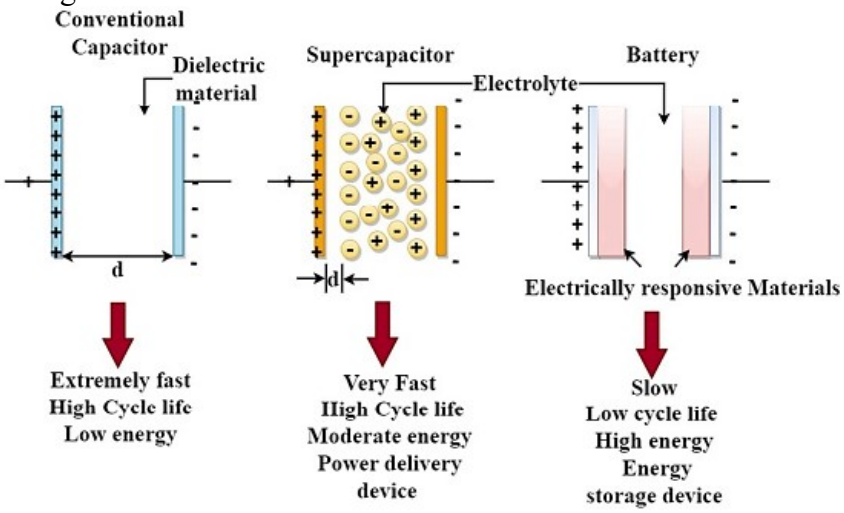

Figure 4. Schematic diagram shows the comparison between capacitor, supercapacitor and battery.

Supercapacitors operate on the same underlying principles and equations as conventional capacitors, however use a more porous structure (activated carbon) and increased electrode surface area to achieve superior capacitance. Consequently, supercapacitors have superior energy density compared to capacitors and enhanced power density relative to Li-ion batteries. Supercapacitors provide rapid charging and have an extended cycle lifespan. This study involves the synthesis of low-cost activated carbon compounds for use as electrode materials to enhance energy density and specific capacitance. Consequently, supercapacitors may possess the potential to replace traditional energy storage devices.

The subsequent sections of the paper are organized as follows: Section 2 examines the pertinent literature on biomass-derived activated carbon and its uses in supercapacitors, establishing a framework for the present study. Section 3 delineates the materials and methodologies used in the investigation, including comprehensive procedures of the activation process and characterization techniques. Section 4 delineates the experimental findings and examines the physical and electrochemical properties of the activated carbon derived from cocoa leaves. Section 5 closes the

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study by presenting major results, consequences, and suggestions for future research, highlighting the scalability and practical applicability of the suggested technique.

2. Review of Literature

Niaz et al., (2024)[24] presented an innovative and sustainable approach that utilizes the unexploited potential of waste biomass, specifically transforming dead leaf petioles from Ficus elastica, an industrial crop known as rubber plants, into high-performance activated carbon (AC) for supercapacitor electrodes via a simple pyrolysis process. The produced activated carbon serves as an electrode material for the construction of symmetrical supercapacitors. It underwent comprehensive morphological and structural investigations using different analytical tools to evaluate the performance and quality of the AC. Electrochemical evaluations using a two-electrode setup with 1 M KOH as the electrolyte demonstrated that the AC electrodes exhibit outstanding properties of electric double-layer capacitance. The result was derived from the analysis of cyclic voltammetry curves that exhibited a rectangular and symmetrical shape throughout scan speeds of 10 to 100 mV/s. At a scan rate of 10 mV/s, these AC electrodes attained a specific capacitance of 128 F/g. The enhanced performance of the AC, relative to other biomass-derived electrode materials, is due to its large surface area and considerable porosity. Furthermore, electrodes fabricated from AC sourced from rubber plants demonstrated exceptional longevity over 10,000 charge-discharge cycles, retaining 89% of their initial capacitance and attaining a Coulombic efficiency of up to 87%. During extended discharge intervals, these electrodes demonstrated a significant specific capacitance, enabling a power density of 200 W/kg and an energy density of 11.4 Wh/kg. This study underscores the feasibility of rubber plant waste in sophisticated energy storage devices and makes a substantial contribution to sustainable materials science. This study provides an eco-friendly method for supercapacitor electrode production, aligning with worldwide initiatives for sustainable energy storage technologies and showcasing the viability of ecologically benign materials in high-performance applications.

Luanwuthi et al., (2024)[25] examined an activated carbon (AC) is increasingly preferred for its remarkable physicochemical properties and its ability to produce electrodes. Nonetheless, research on the environmental and economic ramifications of AC supercapacitor manufacturing has been scarce. This study examined the environmental and economic effects of activated carbon derived from oil palm leaves using hydrothermal carbonization and chemical activation. Experimental procedures were conducted to provide input data for the mass and energy balance, including processing temperature and AC production. A techno-economic study underscores the considerable economic potential of integrating AC generation into biomass processing. Various production sizes, from 720 to 1080 tons annually of oil palm leaves, are evaluated for economic viability. All processes are evaluated based on material and energy balance, accompanied by a comprehensive cash flow analysis to assess profitability criteria. The findings demonstrate that all instances provide positive net present values (NPV), signifying profitability. The cost of air conditioning units is the paramount aspect influencing the economics and feasibility of an air conditioning producing plant. The minimum selling prices (MSP) of AC samples vary between 10.50 and 13.40 USD per kilogram. The life cycle assessment (LCA) utilizes a cradle-to-gate system boundary approach to analyze the environmental sustainability of the system. The ReCiPe 2016 (H) midway impact assessment approach is used to evaluate environmental effect categories. The research indicated that the procedure has environmental repercussions, encompassing marine ecotoxicity, freshwater ecotoxicity, freshwater eutrophication, and human toxicity, mostly attributable to the use of KOH during the chemical activation phase. This study emphasized the economic, environmental sustainability, and waste management advantages of AC generation.

Yetri et al., (2024)[26] examined an agricultural and agro-industrial residues are common byproducts in the forestry sector, and their valorization is a significant concern. Cocoa (Theobroma cacao) pod waste was selected as an activated carbon material and investigated as an active component for supercapacitor electrodes. The carbon electrode was fabricated using 0.3 M and 0.4

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M Potassium Hydroxide (KOH) activators at a temperature of 700°C. The physical characteristics were evaluated by density measurement, X-ray diffraction (XRD), and Scanning Electron Microscopy (SEM), and the electrochemical properties were assessed using the Cyclic Voltammetry (CV) technique. Activated carbon electrodes were fabricated using a mix of chemical and physical activation processes. The process of fabricating carbon electrodes begins with pre-carbonization, followed by milling, chemical activation, pellet formation, carbonization, and concludes with physical activation. The examination of dimensions, density, and specific capacitance in the production of carbon electrodes indicated that the mass, diameter, thickness, and density of the electrodes decreased with the increase of KOH concentrations from 0.3 M to 0.4 M. The specific capacitance of the electrode was directly proportional to the rise in KOH concentration. The XRD measurement results revealed 2θ values ranging from 23.569° to 24.747° for the reflection field 002, and from 44.634° to 44.781° for the reflection plane 100. The X-ray diffraction curve data indicated that the 0.4 M sample at 700°C exhibited a reduced Lc value and lattice distance compared to the 0.3 M sample at the same temperature. Consequently, it may be inferred that the surface area of the 0.4 M sample at 700°C exceeded that of the 0.3 M sample at the same temperature. The electrochemical test indicated that the chemical activation approach at 0.4 M yielded electrodes with superior performance compared to 0.3 M. The specific capacitance measured at a concentration of 0.3 M was 90.2 F/g with a density of 0.850 g/cm³, but at a concentration of 0.4 M it was 140.2 F/g with a density of 0.802 g/cm³. The findings demonstrate the significant potential of activated carbon monoliths derived from agricultural cocoa pods as supercapacitor electrodes.

Gupta et al., (2023)[27] examined the precursor efficacy of Datura stramonium as a bioresource for electrochemical applications. Datura stramonium, also referred to as thornapple or jimsonweed, is a wild and medicinal plant in the Solanaceae family, characterized by the presence of tropane alkaloids. The stem of Datura stramonium was used to manufacture porous activated carbon as an electrode material to evaluate its performance in electric double-layer supercapacitors. The synthesized activated carbon was analyzed for its crystal structure, functional group presence, and textural characteristics using X-ray diffraction (XRD), Raman spectroscopy, Fourier transform infrared (FTIR) spectroscopy, and nitrogen adsorption-desorption isotherms. The study demonstrated that activated carbon had a microporous structure and exhibited BET surface areas of 703 m²/g. The energy-dispersive X-ray (EDAX) spectra of the DSSC sample clearly indicated the presence of carbon (67.53 at%) and oxygen (25.63 at%). XPS examination further revealed the existence of elemental chemical composition. Cyclic voltammetry (CV) was used to investigate the capacitance properties of the synthesized activated carbon. The peak specific capacitance (Cs) measured was 81 F/g for one electrode at a current density of 1 A/g. Consequently, the synthesized new material demonstrates exceptional suitability as an electrode for energy storage devices.

Mehdi et al., (2023)[28] produced activated carbon (AC) materials derived from biochar generated from date seeds by pyrolysis and then activated with H_2SO_4. The study sought to evaluate the efficacy of biochar-based materials for energy storage in supercapacitors by examining the influence of various activation temperatures on their electrochemical performance in an alkaline electrolyte. The emphasis was on determining the most effective content. Raman Spectroscopy and XRD examination indicated that sample DSAC-700 had greater domain organization and optimal storage locations relative to other biochar-based materials. The measured values of the intensity ratio of the D and G bands (ID/IG) for DSBC-600, DSAC-700, DSAC-800, and DSAC-900 were 1.13, 0.83, 1.06, and 1.04, respectively. The minimal (ID/IG) ratio for DSAC-700 signifies a more ordered graphitic structure, enhancing conductivity and ion transport inside the aligned graphitic domains, hence improving electrochemical performance. Samples DSAC-700 had a specific capacitance of 487.5 F/g at a current density of 1 A/g. The trends in galvanic charge and discharge indicated that DSAC-700 exhibited superior charge storage capacity with reduced discharge. The

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biochar-based materials (BC and ACs) obtained from DS shown potential for energy storage applications, marking progress towards sustainable energy solutions.

Murali et al., (2022)[29] studied that porous carbon-based materials represent some of the most promising candidates for future electrochemical energy storage and conversion, being both sustainable and ecologically acceptable. The synthesis of extremely porous carbon materials from biomass has emerged as a prominent area of research. They presented interconnected porous-structured carbon derived from a biowaste precursor. Pine tree (Casuarina) seeds were carbonized using 9 M concentrated sulfuric acid (H_2SO_4), and the resultant pine tree seed carbon (PTC) was activated by combining it with potassium hydroxide in different ratios (1:1, 1:3, 1:5) and conducting straightforward microwave pyrolysis. The pore dimensions and surface area of the produced carbon may be precisely adjusted. The surface area significantly increased with higher KOH concentration, achieving an exceptional specific surface area of 929.9 m2 g−1 at a 1:3 mass ratio. The synthesized porous carbon exhibited a substantial charge storage capacitance of 210 F g−1 at 1 A/g, along with exceptional capacitance retention after 10,000 charge/discharge cycles, even at elevated current densities. The exceptional electrochemical storage properties of hierarchically porous carbon networks stem from the ideal integration of micro- and mesoporous structures, coupled with an increasing number of defect sites at the margins, leading to an augmented surface area and improved conductivity.

Elanthamilan et al., (2022)[30] presented the efficient, cost-effective, and environmentally friendly transformation of waste biomass from Cassia fistula dry fruits into porous activated carbon (CF AC) through KOH chemical activation, and the application of CF AC samples as electrode materials in supercapacitors. The CF AC samples underwent pyrolysis at several temperatures to assess the influence of activation temperature on the capacitive performance of the electrode materials. The synthesized CF AC samples were carefully characterized utilizing a range of spectral and analytical methods, including FTIR, Raman, XRD, BET, XPS, FESEM, EDAX, and TEM examination. The supercapacitor measurements were initially conducted using a three-electrode system, revealing that the CF-800 electrode exhibited the highest specific capacitance of 583 F/g at a current density of 1 A/g, along with a capacitance retention value of 91% after 5000 GCD cycles at the same current density. Consequently, the CF-800 sample was used to construct a CF-800||CF-800 symmetric device. The developed device provided an energy density of 11.11 Wh kg−1, which corresponds to an energy density of 333.3 W kg−1. This finding demonstrated that the activated carbons obtained from the dry fruits of Cassia fistula (CF AC) significantly contribute to the development of cost-effective and efficient electrodes for supercapacitors.

Jain et al., (2021)[31] studied an activated carbons serve as a potential electrode material for supercapacitors (SCs), which are extensively used in commercial applications. This study details the synthesis of a unique activated carbon produced using a cavitation method from a variety of natural European deciduous trees, including Birch, Fagaceae, and Carpinus betulus (often referred to as European hornbeam), used as the electrode material in supercapacitors. The morphological and structural analysis revealed that the synthesized sample had favorable carbon properties, exhibiting significant porosity and a high specific surface area of around 614 $m^2\ g^{-1}$. The electrochemical characteristics of the produced material were assessed using a three-electrode setup in a 1.0 M H_2SO_4 electrolyte. The carbon material has a specific capacitance of 24 F g−1 at 0.25 A g−1 in device mode, demonstrating exceptional cycling stability exceeding 10,000 consecutive charge/discharge cycles. The findings illustrated the straightforward synthesis of biomass-derived carbon and its use as a multifunctional electrode material for supercapacitor applications.

Taer et al., (2021)[32] stated that the comprehensive investigation into the production of activated carbon monolith derived from Tectona grandis leaf biomass waste for supercapacitor electrode materials has been successfully conducted. This investigation was conducted using a mix of chemical and CO_2 activation techniques. Potassium hydroxide served as the activating agent in the chemical activation procedure. The pyrolysis process encompasses carbonization and CO_2

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activation, executed in integrated systems at a temperature of 600°C in a nitrogen gas environment, with CO_2 activation performed at various temperatures: 750, 800, 850, and 900°C. The activated carbon samples derived from Tectona grandis leaves (TL-AC) exhibit distinct morphologies, including carbon rod (750°C), carbon sheet (800°C), and carbon fiber (900°C). The optimal specific capacitance of the TL-AC samples reached 168 F g−1 in a 1 M sulfuric acid solution with a two-electrode arrangement. This study presented an economic methodology essential for the development of electrode materials with varied architectures for energy storage systems using available resources.

Taer et al., (2020)[33] emphasized contemporary laboratory-scale techniques for synthesizing activated carbon nanostructures from leaf biomass waste. Four categories of concentrated leaf waste are acacia leaves, pineapple leaves, Terminalia catappa leaves (TCL), and Pandanus tectorius leaves (PTL). Waste leaves were transformed into activated carbon using KOH activation and a one-stage combined process of carbonization and physical activation. Symmetric supercapacitor electrodes were fabricated in a sandwich-type monolithic form without the need of adhesive materials. In this research, nanofiber structures predominated the surface morphology of carbon monolith, particularly in acacia leaves, pineapple leaves, and TCL. Remarkably, the same fundamental material of TCL may yield two distinct nanostructures: nanofiber and nanosheet. Furthermore, the percentages of carbon and oxygen content in the sample were also shown. Moreover, the supercapacitor cells demonstrated the greatest specific capacitance, with activated carbon produced from pineapple leaves reaching 150 F g−1 in a 1M H2SO4 aqueous electrolyte at a low scanning rate of 1 mV s−1. Ultimately, our findings validated that leaf biomass waste had significant promise as a precursor for activated carbon nanofiber/nanosheet structures suitable for supercapacitor electrodes.

Srinivasan et al., (2019)[34] studied an activated carbon (AC) samples obtained from Polyalthia longifolia seeds (PLS) were synthesized at several temperatures (600, 700, 800, and 900 °C) using the pyrolytic chemical activation method. The synthesized PLS-ACs were analyzed using spectral and analytical techniques. The electrochemical characterization was conducted using cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and impedance spectroscopy methods. A three-electrode system was established, including the as-prepared PLS-AC samples coated on nickel foil (working electrode), Ag/AgCl (reference electrode), and Pt-wire (counter electrode) in 1 M sodium sulfate (Na_2SO_4). A specific capacitance (Csp) of 365 Fg−1 was attained at a current density of 1 Ag−1 for the PLS-AC sample pyrolyzed at 900 °C, demonstrating 92% retention after 5000 charge/discharge cycles, hence confirming substantial recycling durability. Moreover, the notable electrochemical behavior within the specified voltage range corroborated its capacitive characteristics. The economical, high-performance carbon compounds derived from bio-waste demonstrated improved supercapacitance, making them ideal for energy storage systems. Additionally, the engineered symmetric device using PLS-9 demonstrated an energy density of 27.5 Wh kg−1 at a power density of 499 W kg−1. Consequently, the very porous PLS-9 electrode was identified as a suitable option for high-performance supercapacitors.

3. Material & Methods

The purpose of this research is to study on a preparation of activated carbon generated from cocoa leaf that is both more environmentally friendly and less costly. This preparation is used in the creation of electrode materials for supercapacitors. The purpose of this research was to explore the process of producing activated carbon from cocoa leaf via the use of carbonization, chemical activation, and physical activation with the carbon dioxide. The cocoa leaves are first activated chemically using potassium hydroxide (KOH), then carbonized at 600 degrees Celsius in nitrogen dioxide (N2) environment, and finally activated at a higher temperature in carbon dioxide atmosphere. By exhibiting high specific capacitances together with high energy and power densities,

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the activated carbon that was synthesized was able to increase the electrochemical performance of a two-electrode configuration.

In this particular investigation, cocoa leaves (CL) were employed as a source of raw material. After being sun-dried for two days, the cocoa leaf was then dried in an oven at a temperature of 110 degrees Celsius for forty-eight hours. Once the leaves had been dried, they were pre-carbonized at 250 degrees Celsius for a period of 2.5 hours. After being heated in a hot plate stirrer for two hours at a temperature of 80 degrees Celsius, the carbonized samples were combined with potassium hydroxide (KOH) at a concentration of 0.5 M in 150 milliliters of distilled water. A monolith was formed from the activated sample by utilizing a hydraulic press at a pressure of eight metric tons. After that, the sample was carbonized at 600 degrees Celsius in an environment of nitrogen dioxide, and then it was activated in carbon dioxide at 850 degrees Celsius for two and a half hours at a rate of ten degrees Celsius per minute. A visual representation of the procedure for preparing the CL sample may be seen in Figure 5.

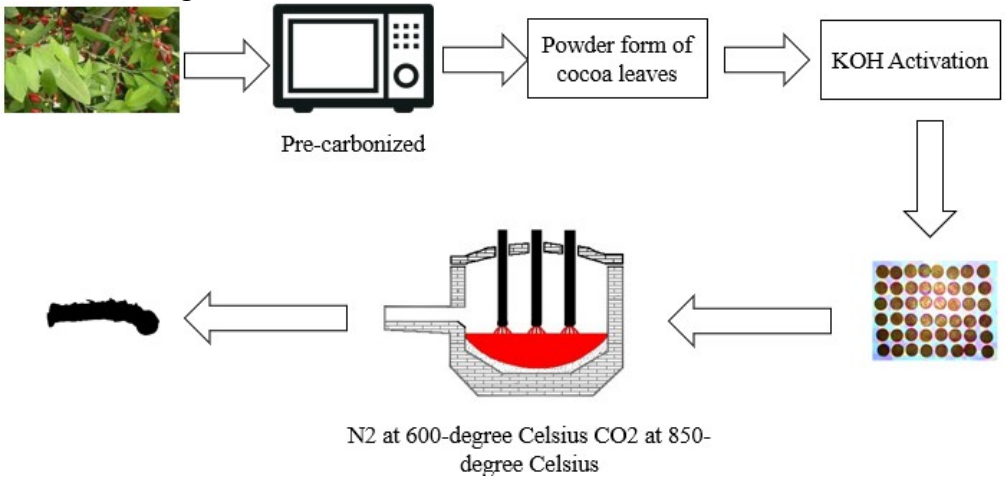

Figure 5. The CL samples preparation process.

As part of this research, the physical parameters and electrochemical characteristics of the CL sample were under investigation. At both the beginning and the end of the activation process, many physical characteristics including mass, diameter, thickness, and density were determined. The cyclic voltammetry (CV) and galvanostatic charge/discharge (CV) measurements of CL have been evaluated in order to determine their electrochemical properties. A two-electrode setup in a solution of 1 M H_2SO_4 has been used for the purpose of these measurements.

4. Result and discussion

Figure 6 display the shrinkage of physical parameters of CL samples before and after physical activation. After the physical activation process, the physical parameters include mass, diameter, thickness, and density of the CL samples have been shrinkage. The shrinkage percentage of the mass, diameter, thickness, and density are 76.47%, 29.38%, 28.57%, and 38.04%, respectively. The release of non-carbon materials when the physical activation takes a place, causing the shrinkage of the physical parameters [35][36].

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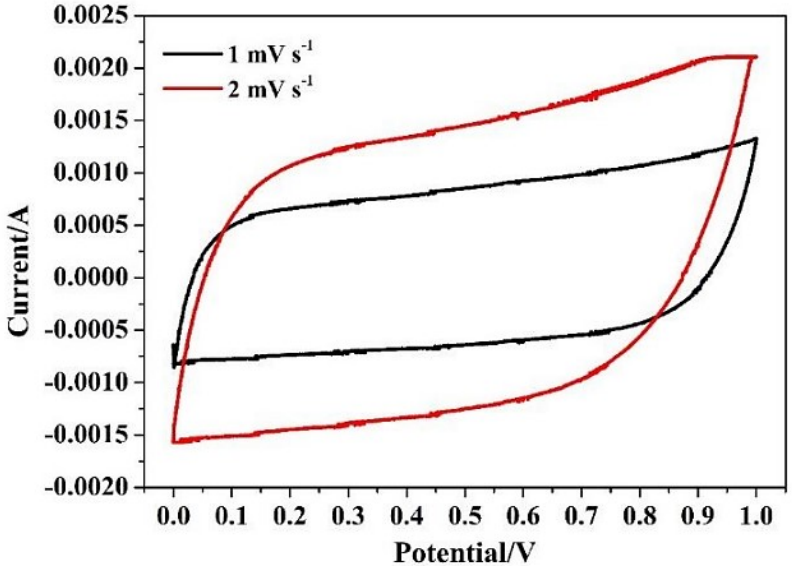

Figure 6. CL samples at different scan rates

In a setup consisting of two electrodes, CV and GCD measurements were used in order to evaluate the electrochemical performance of the CL sample. The CV curves of a CL sample that were obtained at scan rates of 1 and 2 mV/s are displayed in Figure 6. It should come as expected that the CV curves maintain their quasi-rectangular form regardless of the scan rate. On the basis of the CV curve, the specific capacitance of CL was determined by using Equations (1):

$$C_{sp} = \frac{I_c - I_d}{s \times m} \quad (1)$$

Where C_{sp} is specific capacitance (F/g), I is current (A), s is scan rate, and m is average mass of electrode (g). The specific capacitance of CL are 119 F/g and 108F/g, respectively. It outperforms carbon-based electrodes as compared to our previous study such as [37][38] and [39].

The particular capacitance of the CL sample is shown in Figure 7, which demonstrates the effect of different scanning speeds. At increasing scan rates, the specific capacitance of the CL sample has reduced. This may be ascribed to the fact that the CL sample has a pore structure and bigger micropores, in addition to the comparatively short diffusion time that ions take from the mesopores to the micropores [40].

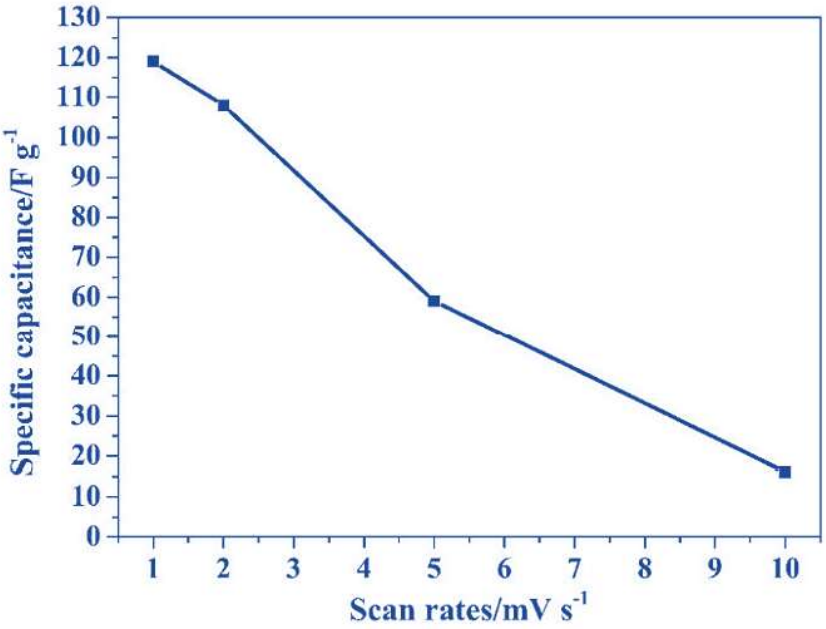

Figure 7. Specific capacitance versus scan rates.

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Figure 8 shows the GCD curve of the CL sample. Noticeably, the lower relative IR drop (0.943 V) suggests a low equivalent series resistance (ESR). The specific capacitance of CL from the GCD curve was calculated by the Equations (2):

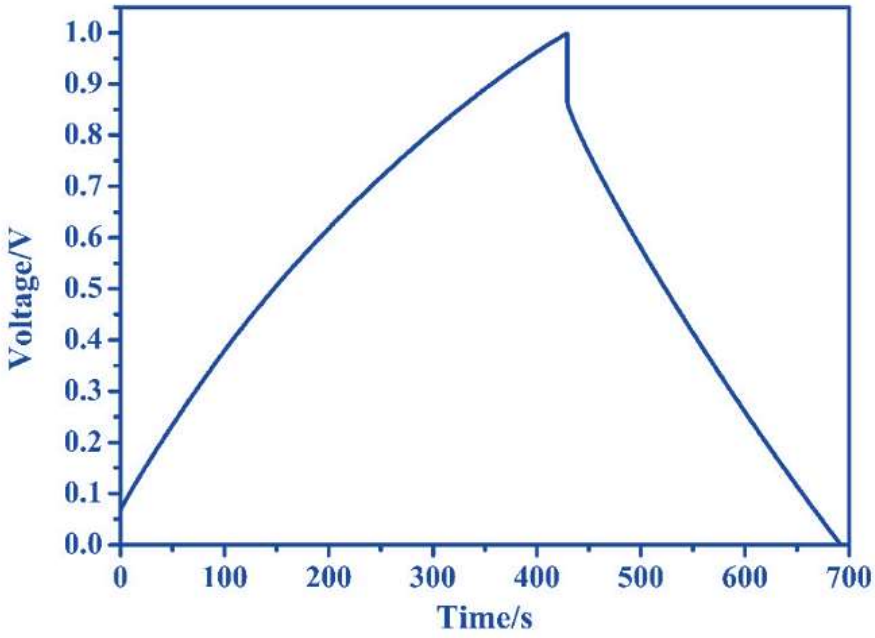

Figure 8. GCD curve of the CL samples at constant current

$$C_{sp} = \frac{I \times \Delta t}{m \times \Delta V} \quad (2)$$

Where C_{sp} is specific capacitance (F/g), I is current (A), s is scan rate, and m is average mass of electrode (g), and Δt is discharge time (s), and ΔV is voltage (V). The calculated specific capacitance based on GCD curve was estimated to be 210 F/g at constant current 1 A. The energy and power densities of CL sample were calculated by the equations (3).

$$E = \frac{1}{2} C V^2 \times \frac{1}{3.6} \quad (3)$$

$$P = \frac{E}{\Delta t} \times 3600 \quad (4)$$

Where E is energy density (Wh/kg), P is power density (W/kg), C is specific capacitance (F/g), V is voltage (V), and Δt is discharge time (s). The energy and power densities of the CL samples were calculated by equation (3) and (4) are 29.7 Wh/kg and 39.9W/kg. It is worth noting that the assembled CL samples exhibit a higher energy density of 29.7 Wh/kg, higher than other existing biomass-based carbon electrode for supercapacitors [39].

5. Conclusion and future work

In this work, the possibility of employing cocoa leaves as a raw material for the production of activated carbon that is acceptable for use in supercapacitor electrodes is successfully shown. A considerable increase in the material's characteristics is achieved by the process, which involves chemical activation using potassium hydroxide (KOH) as well as physical activation under regulated circumstances. A specific capacitance of 210 F/g, an energy density of 29.7 Wh/kg, and a power density of 39.9 W/kg are all achieved by the activated carbon that has been created, which is superior to many of the carbon materials that are currently based on biomass. Activated carbon generated from cocoa leaves has the potential to be an environmentally benign and cost-effective option for energy storage applications, as shown by these studies. Optimization of the activation process and scalability for industrial applications should be something that will be investigated in further study.

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