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Biodegradable Activated Carbon Material Derived from Eggplant Waste for Enhanced Supercapacitor Performance

Journal of Electrical Systems

Abstract: - Agricultural-waste-derived porous carbon and vegetable-waste-derived porous carbon materials have been extensively studied as electrode materials for high-performance supercapacitors due to their abundance and ability to be consistently reproduced. This paper focuses on utilizing eggplant waste, the primary by-product, as a precursor for producing porous carbon through the easy carbonization and activation process. The resultant porous carbon is then employed as an electrode material for supercapacitors. The Eggplant waste-derived porous carbon exhibits a notable surface area of 1095.4 $m^2 g^{-1}$. This carbon material possesses the benefits of being cost-effective and environmentally friendly while exhibiting superior electrochemical performance in comparison to materials obtained from agricultural waste. The carbon electrode made from eggplant demonstrates an energy density of 9.19 Wh Kg^{-1} and a power density of 2880 W Kg^{-1}, indicating its outstanding energy storage capacity.

Keywords: Eggplant Waste, Biodegradable Materials, Activated Carbon, Supercapacitor Device.

I. Introduction

Research indicates that around one-third of the vast quantity of food available for human consumption is wasted globally [1]. With abundant agricultural resources, India generates 50 metric tons of vegetable waste, or approximately 30% of its whole production [2]. The eggplant, also known as aubergine, brinjal, or baigan, is a plant species belonging to the family Solanum melongena L. It originated in India and is a highly significant and productive agricultural crop that is also economical. It is commonly planted and cultivated in many regions worldwide, serving as a popular vegetable. According to FAO statistics [3], the global production of this crop reached 52.3 million tons in 2016 [4]. Eggplant waste is a substantial amount of biodegradable material generated by humans. Unfortunately, a significant portion of this waste is discarded in open areas, where it decomposes and contributes to the spread of diseases and health problems. However, burning this waste releases harmful chemicals such as carbon monoxide, hydrocarbons, and nitrogen oxides, which contribute significantly to the destruction of tropospheric ozone [53]. In addition, the inadequate storage capacity of vegetables and improper processing and packing of eggplant vegetables based on customer requirements and specifications also contribute significantly to waste creation. Eggplant waste refers to not only the spoiled portion of the vegetable, but also includes the damaged, scraped pieces, peels, and/or slurries that have no economic value. Converting food waste into electricity is an effective way to conserve resources and sustainably ensure environmental safety, as food waste is relatively inexpensive.

Activated or porous carbon (PC) is a type of carbon that cannot be converted into graphite. Artificial carbon compounds are currently utilized in various fields like energy storage, fuel cells, and water purification. These carbon materials provide numerous appealing characteristics, such as abundant sources of production (e.g., agricultural wastes and residues, vegetable wastes), high conductivity, excellent physical and chemical stability,

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and porous structures [16]. The demand for clean energy storage has been crucial for several decades. One remarkable invention is the supercapacitor. These capacitors are a new generation of classic capacitors that have an exceptional energy density. They have been widely accepted as promising energy storage devices that can fill the gap between conventional capacitors and batteries. These substances have garnered notable attention owing to their aptitude to generate a large amount of electricity in a small space, their ability to be used for a long time without deteriorating, and their positive impact on the environment [5]. Supercapacitors provide certain benefits compared to batteries, as they store energy in the form of electric charge at the interface of electrolyte-porous carbon [6]. Although supercapacitors are well-suited for rapid energy storage and release, a significant gap remains to be bridged to attain these devices' desired energy and power densities. Different types of supercapacitors are shown in Fig. 1.

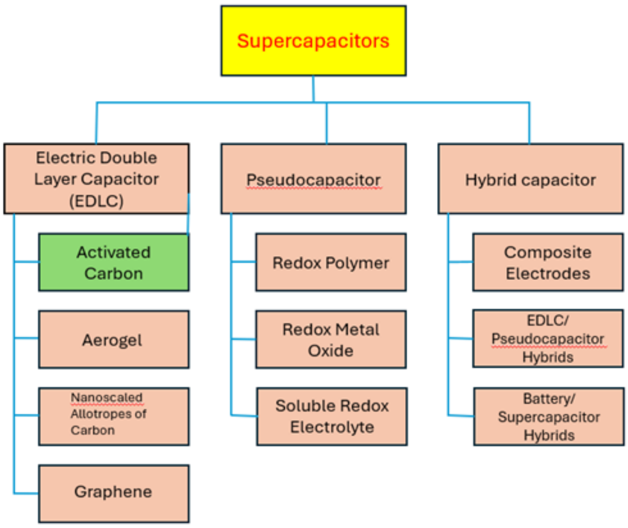

Fig. 1. Types of supercapacitors

II. TYPE STYLE AND FONTS

A supercapacitor typically comprises a cathode and anode, together with an electrolyte solution that facilitates the transmission of electrons, based on its energy-storage mechanism. There are two categories of capacitors: Electric Double-Layer capacitors (EDLC), often known as symmetric supercapacitors, and Asymmetric supercapacitors (ASC). For example, the symmetric structure of a supercapacitor is displayed in Fig. 2. These categories depend on the method of assembly or manufacture. EDLCs primarily depend on the electrostatic interaction between the electrode surface and the electrolyte ions. The fabrication of high-quality electrodes and electrolytes is crucial in the production of a supercapacitor.

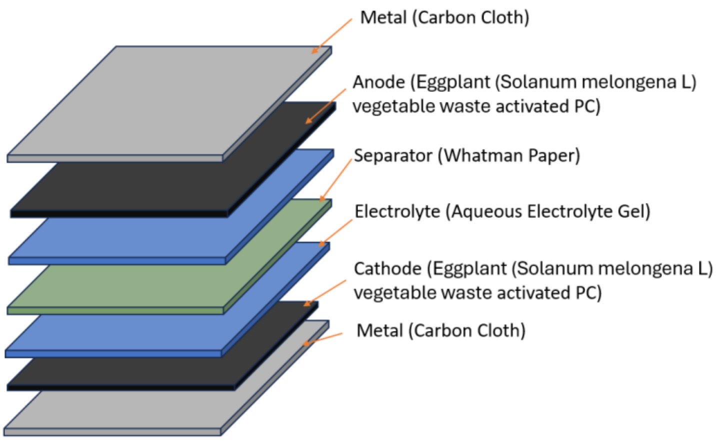

Fig. 2. Structure of symmetric supercapacitor

Porous carbon materials are suitable candidates for EDLCs due to their extremely high surface area, outstanding desorption characteristics, and superior electrical conductivity. Scientists are actively exploring novel approaches and techniques to enhance the energy density and power density of supercapacitors. In recent times, researchers have successfully created nanostructured materials using biomass resources for energy storage, specifically in the realm of supercapacitor electrodes [7]. The electrode material utilized in a supercapacitor is the most crucial and significant component since it determines the total performance of the produced supercapacitor [8]. Therefore, ongoing research is being conducted to investigate novel electrode materials to achieve enhanced performance [9]. Recent studies have proposed using various agricultural waste materials, such as rice husks [10], marigold flowers [11], areca palm leaves [12], banana bract [13], bean dregs [14], camellia seed shells [15], corn husks [16], corn stalks [17], corn starch [18], corn stover [19], corn straw [20], corn cob [21], chicken bone [22], crab waste [23], eggshell [24], fungus bran [25], herbal plant flowers [26], jackfruit peel [27], cow dung [27], lotus seed [28], mangosteen peel [29], mung bean husk [30], natural wood [31], onion peel [32], palm kernel [33], peanut shells [34], pinewood chips [35], walnut shells [35], lotus leaves [35], pineapple waste [36], potato peel [37], poultry waste [38], rice straw [39], soybean waste [40], soybean pod [41], sword bean shell [42], tea waste [43], tobacco straw [44], bagasse waste [45], waste filter paper [46], and wheat straw [47], as raw materials for producing electrode materials for power sources. This is an innovative approach that can transform agricultural waste materials into useful resources. The outstanding features of electrode-based EDLCs created from agriculture waste/vegetable waste include their non-toxic nature, high power capabilities, and low cost [48]. Furthermore, the pore size and surface area of these electrode materials are crucial factors in choosing the appropriate material for supercapacitors. Specifically, the high surface area and controlled distribution of pore sizes in carbon materials determine the interface between the electrode and electrolyte, thus impacting the performance of the supercapacitors [49]. Conversely, to address the worldwide economic challenges resulting from coal and fossil fuels, there is a significant focus on electrode material made from agricultural and vegetable waste.

The increasing need for adaptable electronic devices motivates us to seek a renewable energy source to supply power to these intelligent electronic devices [50]. Therefore, energy storage devices like supercapacitors play a vital role in powering smart electronic devices due to their extended lifespan, rapid charging and discharging capabilities, and exceptionally high-power density [51].

This study utilized dehydrated Eggplant (Solanum melongena L) food waste to produce porous carbon composite materials. The dried veggies performed a simple procedure of carbonization and activation at high temperatures. The resulting carbon material is porous and has a large surface area and pore volume. It exhibits a multi-pore texture composed of many layers of pores. Due to their distinctive composition, carbon materials possess exceptional electrochemical properties that make them ideal for constructing electrodes in supercapacitors.

II. Experimental Section

Materials Used:

Eggplant (Solanum melongena L) vegetable waste that is decomposing and smashed is collected from KL University's hostel kitchen and the local municipal market dustbin. The carbon fabric was purchased from AvCarb in the United States. Isopropyl Alcohol (IPA), ethanol 99.9%, PolyVinylidene DiFluoride (PVDF) (homopolymer powder, M.W.~320,000), N-methyl-2-pyrrolidone (NMP), sulphuric acid (H2SO4, 98%), polyvinyl alcohol (PVA) (M.W.~125,000), and hydrochloric acid (HCl) 35-38% were used as received. Whatman® qualitative filter paper grade 1 (dia. 125 mm) purchased locally was employed as a separator in the lab-scale Supercapacitor. De-ionized (DI) water was utilized for the entire work.

Material Synthesis:

Untreated eggplant (Solanum melongena L) that was rotten and deformed was washed with water and cut into smaller pieces. It was then dried at room temperature several times and transformed into separate powders using a 75-watt mixer. The powders were thereafter placed in a zirconia crucible. Microscopic punctures were created to eliminate volatile substances while heating and reduce the interaction with oxygen. The dried specimen is then heated to a temperature of 800° C for 50 h to obtain carbonized flakes, which are subsequently ground to obtain a fine powder. The above-obtained samples of 5 g were mixed with an equal amount of $ZnCl_2$. Subsequently, the produced sample was placed in an environment of argon gas with a flow rate of 100 ml/min and a pressure of 1 to 2 kg/cm^2. This was done to facilitate carbonization using a tubular furnace that had an inert gas supply. The system temperature is kept at an increasing pace of 5° C/min to 800° C and maintained at the same temperature for 2 h and then allowed to cool down to room temperature to take out the sample from the tubular furnace. The produced char sample is retained and stirred in a beaker containing 1M HCl for 2 h. The resultant mixture is then filtered using distilled water and ethanol. Subsequently, the sample is placed in a hot air oven at a temperature of 500° C for 20 h, resulting in the obtained sample. The substance produced by the activation and carbonization procedure will be referred to as AC-Eggplant or Porous Carbon (PC).

Device Fabrication:

The working electrode mass of the electrode was calculated to be around 2.6 mg/cm$_2$. To fabricate a symmetric supercapacitor current collector or electrodes, 2.6-4.2 mg of PC was mixed with carbon black and PVDF (M.W.~ 320,000) in an agate mortar at an 8:1:1 weight ratio and stirred for 30 min. Several NMP drops were added to the mixture until a slurry was formed. The mixture is then used to coat each electrode with roughly 2.6 mg of coating using a brush, which produces symmetry within them. To eliminate water, the porous carbon-coated electrodes remained dried overnight in a vacuum oven at 50° C for approximately 12 h. The dried electrodes were then removed from the vacuum oven. In this way, electrodes are prepared. Following that, PVA/H_2SO_4 electrolyte was produced using the procedure described in [52]. 1 g of PVA was mixed with 10 ml of DI water and stirred for 12 h using a magnetic stirrer. Then, add 1.18 ml of H_2SO_4 dropwise to the PVA gel and mix for 1 h to create a PVA/H_2SO_4 gel electrolyte. The dried electrode and polymer electrolyte layer are cut into 1 cm×1 cm dimension and inserted between two freshly produced porous carbon electrodes, and hence our supercapacitor device is fabricated and assembled. The complete steps of the synthesis of porous carbon material derived from Eggplant waste and the fabrication process of the electrode are schematically shown in Fig. 3.

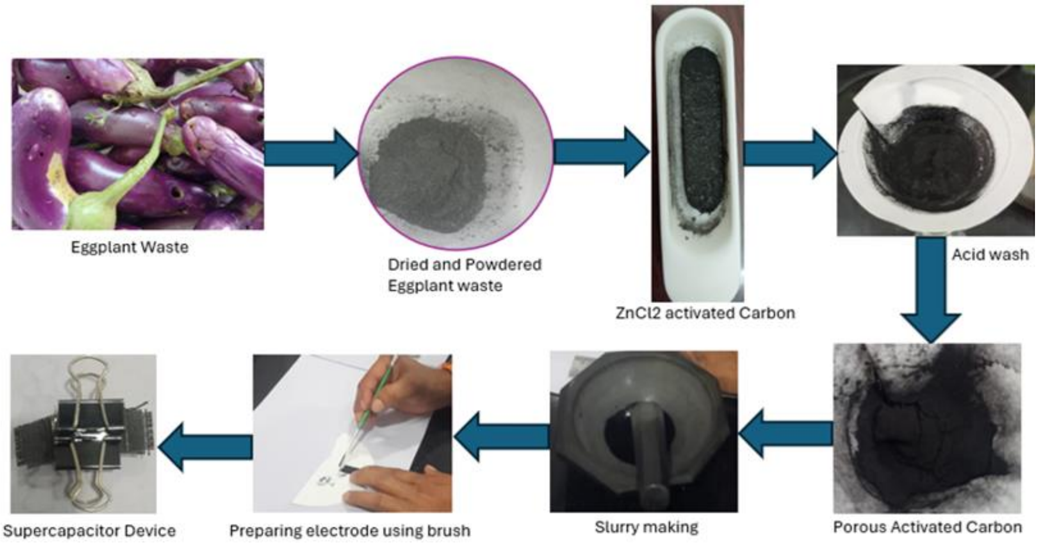

Fig. 3. Fabrication process of electrodes with porous carbon material derived from areca Eggplant waste through one-step carbonization and an activation process

III. Prepare Your Paper Before Styling

Characterization and Electrical Measurements:

The structural characteristics and crystallinity were studied using X-ray diffraction (XRD) (Xpert Pro, Panalytical). The surface morphology was investigated by FESEM (Zeiss Gemini 1Sigma 300). The Raman Spectroscopy investigations were conducted utilizing a Renishaw InVia microscope. The surface area of the synthesized samples was measured and calculated using a surface area analyzer (BEL SORP mini II, Microtrac Bel). The Pore size distribution was calculated according to the Barrett-Joyner-Halenda (BJH) method from BET data. The electrochemical behavior was evaluated in the full-cell format through an electrochemical workstation (PARSTAT PMC 2000A) that performed CV, GCD, and EIS analyses. The specific capacitance of the supercapacitor electrodes (C, F/g or F g^{-1}) and symmetrical supercapacitor device has been calculated using the following Equation

$$C = \frac{I \, X \, \Delta t}{\Delta V \, X \, m_{ac}}$$

Where I = discharge current, Δt = discharge time, ΔV = Potential Voltage, and mac = Weight of the active material including the binder.

Energy density (E, Watt-hour/Kg) was calculated using the below equation

$$E = \frac{C \, X \, (\Delta V)^2}{2} \, X \, \frac{1000}{3600}$$

Power density (P, Watt/Kg) was calculated using the below equation

$$P = \frac{E \, X \, 3600}{\Delta t}$$

The specific capacitances were calculated from the CV curves using the below equation

$$C = \frac{\int_{V_i}^{V_f} I(E)dE}{m.\upsilon.(V_i - V_f)}$$

Where V_i=initial voltage in the CV curve
V_f = final voltage in the CV curve
υ = is the scan rate (Volts/Sec)
m = weight of the active material in the electrode
V_i -V_f = width of the potential window

III. Results and discussion

Fig. 4. shows the microscopic SEM image of activated carbon from eggplant waste at different magnifications. It is seen from the figure that the carbon particles are filled with pores and voids with increased surface roughness. The XRD pattern in Fig. 5 a) confirms the presence of the graphitic phase of carbon. The 2θ values at around 23.8° and 43° correspond to the graphitic carbon's (002) and (100) planes, respectively. The graphitic phase is a conducting form of carbon that is believed to help reduce resistance during the electrochemical process. The two peaks showed broader profiles, that indicate an amorphous structure in porous carbon. It has been reported that, as compared to graphitic structures, amorphous structures can provide larger channels for the transport of electrolyte ions, hence increasing the rate capability of supercapacitors [52].

Raman spectroscopy is used to estimate the defect degree of the porous carbon sample because of its high sensitivity. The obtained results are shown in Fig. 5 (b) & (c). In that, two characteristic peaks were identified, corresponding to the D-band (1339 cm^{-1}) and the G-band (1595 cm^{-1}). It is worth noting that the presence of defects helps to absorb more ions, increasing the capacity given by faradaic processes, and improving double-layer capacitance by modifying the surface structure.

Fig. 6. displays the N_2 adsorption-desorption isotherm for eggplant char. Eggplant Char has a calculated Brunauer-Emmett-Teller (BET) surface area of around 1095.4 m^2 g^-1. The BET analysis found that Eggplant Char includes nanopores, with a total pore volume of 0.676 cm^3 g^{-1} and an average pore size of around 2.4686 nm.

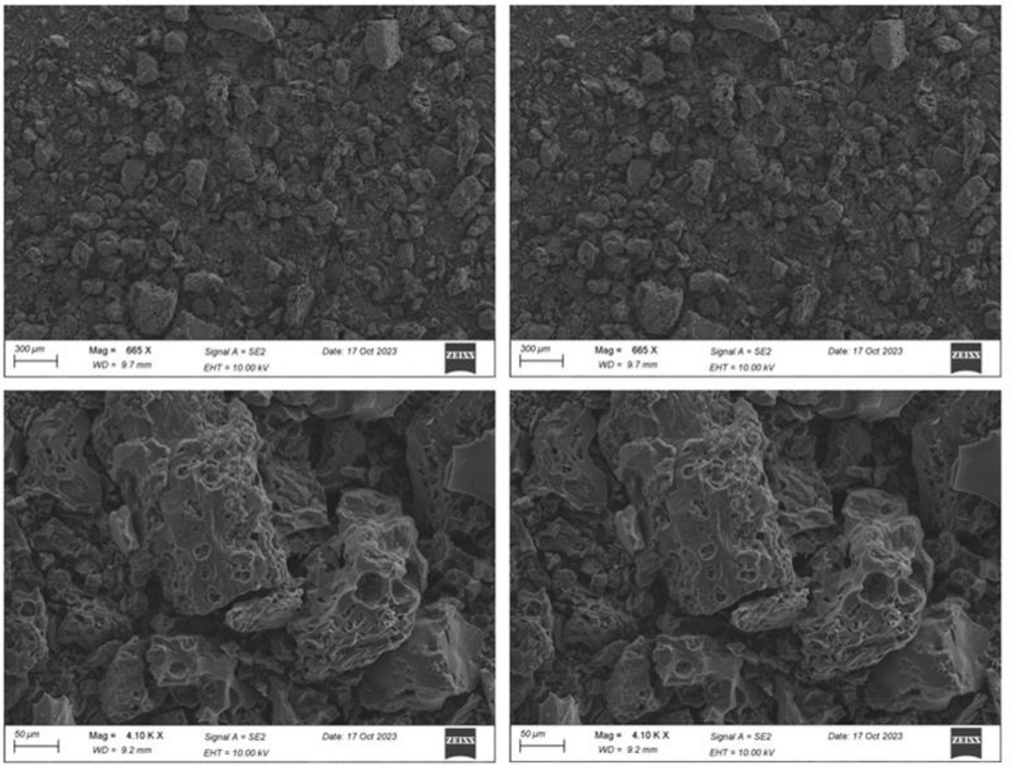

Fig. 4. SEM images of Eggplant waste derived carbon material at different magnifications

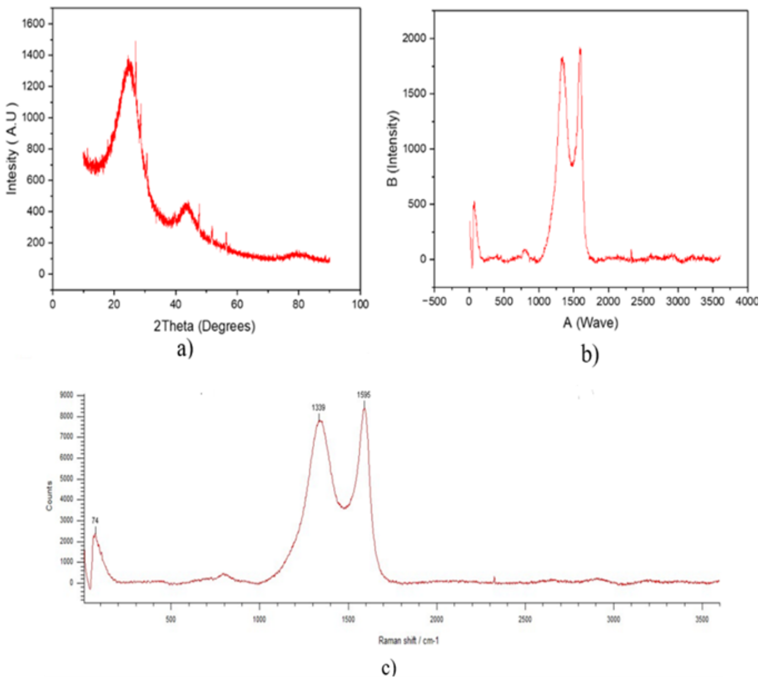

Fig. 5. a) XRD spectra b) Raman Spectra c) detailed Raman Spectra

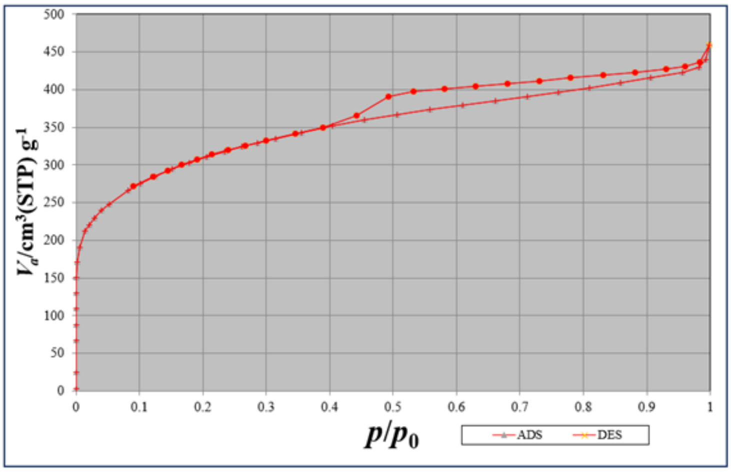

Fig. 6. N2 adsorption-desorption isotherm of eggplant char

A supercapacitor with a two-electrode structure of symmetric type was constructed by inserting two electrodes separated by an ion-transporting layer and tested in a 1 M H_2SO_4 aqueous electrolyte. Fig. 7a depicts the CV profile of the electrode in the device configuration, which has a rectangular shape and no redox peak even at high scan rates, confirming the device's high-rate performance and seamless double-layer charge storage at the electrode/electrolyte interface. Fig. 7b depicts the galvanostatic charge-discharge (GCD) profile at various current densities, ranging from 1 mA to 15 mA. The charge-discharge curve patterns indicated highly symmetric, and there was no voltage drop observed even at high current density, which indicates the synthesized material had good electrochemical properties even under higher charge-discharge current circumstances. That energy was stored on the electrode mainly via physical adsorption forming double charge layers. The result we have obtained is closely related to the results of the CV curve measurements (Fig. 7a). At a current density of 1 mA g^{-1}, the maximum capacitance is 362.36 F g^{-1}.

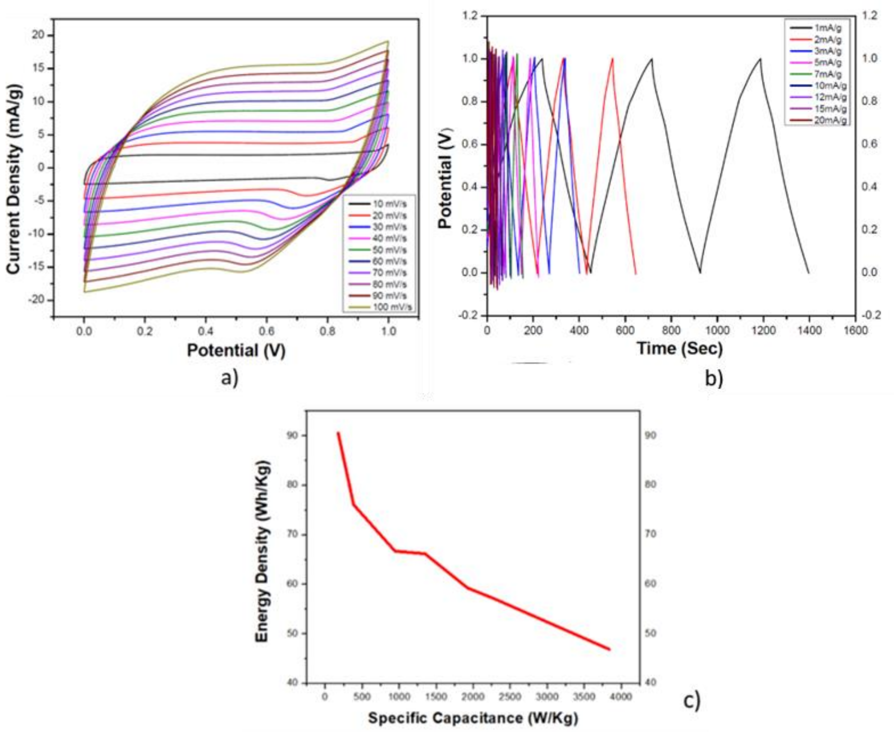

Fig. 7 a) CV curves of sample at multiple scan rates, b) GCD curves of sample at various current densities and c) Ragone plot of sample

It is noted that the specific capacitance gradually decreases from 362.36 F g^{-1} to 184.4 F g^{-1} if current density is increased from 1 mA g^{-1} to 15 mA g^{-1}, maybe due to insufficient time for electrolyte ions to reach the electrode pores. In addition to that, we also observed that the discharge duration reduces as the current density increases from 1 mA g^{-1} to 15 mA g^{-1}. A voltage decrease of 0.9 V was seen at 1 mA g^{-1} and from 1 V to 15 mA g^{-1}. Fig. 7c displays the Ragone plot of the char sample, energy density vs specific capacitance. Following the determination of specific capacitance, we determined energy density and power density, as shown in Table 1 below. The energy density can be increased by raising the specific capacitance and usable operating voltage. Specific capacitance with varied current density is shown in Table 2.

Material	Specific Surface Area (sqm/g)	Specific Capacitance (F/g)	Energy Density (Wh/g)	Power Density (W/Kg)	Reference
PALM KERNEL WASTE	776.4	222	27.9	85.7	[33]
CORN STALK WASTE	408	125	15.3	89	[17]
FUNGUS BRAN	1623	333.25	6.09	250	[25]
MANGOSTEEN PEEL WASTE	2623	357	17.28	401	[29]
POTATO PEEL WASTE	Not Given	323	45.5	800	[37]
SWORD BEAN SHELL WASTE	2917	264	12.5	1000	[42]
CORN STOVER WASTE	1607	310	43	1990	[19]
POULTRY WASTE	444	520	23	2150	[38]
SOYABEAN CURD RESIDUE WASTE	215	Not given	9.95	2360	[40]
SOYABEAN POD WASTE	1807	366.1	8.34	2470	[41]
In this work (EGGPLANT WASTE)	**1095.4**	**184@15mA**	**6.4**	**2880**	This work

Table 1 Comparison of specific surface area, specific capacitance, energy density, and power density of carbon-based electrode materials derived from Eggplant.

Current Density (mA/g)	IR Drop (V)	Discharge Time (s)	Capacitance (F)	Specific Capacitance (F/g)
1	0.9	212	90.59	362.36
2	0.98	98	76.1	304.4
5	1	34	66.71	266.71
10	1	15.44	66.2	264.8
12	1	12.4	57	228
15	1	8	46.1	184.4

Table 2 Comparison of specific capacitances of carbon-based electrode materials derived from Eggplant.

IV. CONCLUSION

Biodegradable eggplant waste was converted into porous carbon using a simple method of carbonization and activation processes, which was then used as electrode material in a supercapacitor device. The resultant porous carbon has a huge surface area (1095.4 m^2 g^{-1}). This carbon electrode made from eggplant has a high specific capacitance of 2880 WKg^{-1} at 15 mA and an energy density of 9.19 Wh Kg^{-1} at 7 mA. The capacitance performance of this symmetrical cell was also tested against a two-electrode cell using CV curves at scan speeds ranging from 1 to 15 mV s^{-1}. When the scan rate increases, the rectangular pattern observed remains unchanged, indicating a rapid charge-discharge process. Compared to agricultural waste-derived products, this activated carbon material has the advantages of being economical, environmentally friendly, and having a high power density.

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