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*by Rika Taslim*

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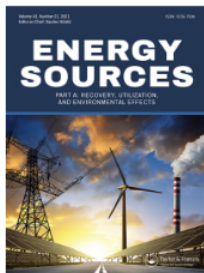
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# Sustainable development of biomass-derived activated carbon through chemical and physical activations and its effect on the physicochemical and electrochemical activity

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## ABSTRACT

Activated carbon derived from biomass waste and their application as supercapacitor electrodes have aroused a considerable research interest in recent years. In this work, we demonstrate the use of *Coffea canephora* leaf (CCL) waste for the preparation of activated carbon as supercapacitor electrodes via chemical activation with straightforward pyrolysis at high temperatures for the first time. Potassium hydroxide with three different concentrations, i.e. 0.1 M, 0.3 M, and 0.5 M, was used as activating agent. The as-prepared activated carbon using 0.3 M KOH (CCL-0.3) displayed good physicochemical properties and exhibited superior electrochemical performance than the other two samples (0.1 and 0.5 M). CCL-0.3 achieved the specific capacitances of 297 F g<sup>-1</sup> and 220 F g<sup>-1</sup> at 1 A g<sup>-1</sup> in 1 M H<sub>2</sub>SO<sub>4</sub> and 1 M Na<sub>2</sub>SO<sub>4</sub> electrolytes, respectively. Moreover, CCL-0.3 in 1 M H<sub>2</sub>SO<sub>4</sub> exhibits the equivalent series resistance ( $R_s$ ) and the charge transfer resistance ( $R_{ct}$ ) value of CCL-0.3 in 1 M H<sub>2</sub>SO<sub>4</sub> of 0.73  $\Omega$  and 4.9  $\Omega$ , respectively. Additionally, this study provides strategies for preparing activated carbon as supercapacitor electrode materials with superior performance via chemical activation with straightforward pyrolysis for the renewable energy storage devices.

## ARTICLE HISTORY

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## KEYWORDS

*Coffea canephora* leaf; activated carbon; chemical activation and straightforward pyrolysis; electrode materials; supercapacitor

## Introduction

The growing requirement for green, clean, effective, and renewable energy storage equipment has become rising importunate owing to the overuse of fossil fuel consumption and their environmental impact (Wu et al. 2021). To solve these problems, the development of energy storage systems with eco-friendly features and high performance has aroused a tremendous research attention (Wang et al. 2020). In the area of electrochemical energy storage systems, supercapacitors (SCs) or ultracapacitors as backup power sources, advanced energy storage systems, and energy conservation have gained widespread attention over the past few years. SC devices have been employed for various uses, such as electric vehicles, portable electronics, and biomedical equipment.

Owing to their availability, sustainability, renewability, and eco-friendly properties, biomass materials as SC electrodes have become an alternative for meeting the need for sustainable and green carbon sources for further development of SC electrode materials (Amakoromo et al. 2021). For the development of SC electrodes based on biomass waste, much progress has been made in this research field. For example, *Tectona grandis* leaf (Taer et al. 2021) and many biomass wastes including kenaf (Park et al. 2021), sugarcane tip (Wei et al. 2021), green steam of cassava (Taer et al. 2021), bamboo leaf (Jayachandran et al. 2021), *Sapindus trifoliatus* nutshells (Vinayagam et al. 2021), cashew nutshell

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(Merin et al. 2021), rotten potato (Wang et al. 2021), pecan shell (Zhang et al. 2022), *Allium cepa* peel (Ali et al. 2021), citrus peel fiber (Mondal, Kumar, and Kanti 2021), *Acacia auriculiformis* (Bhat et al. 2021), *Caesalpinia Sappan* (Bhat et al. 2022), and birchwood (popsicle sticks) (Selvaraj et al. 2022) have been employed as alternative carbon sources for SC devices. All of the carbon sources noticed above are inexpensive, sustainable, eco-friendly, and show great performance to be used as SC electrode.

In the present work, we used *Coffea canephora* leaf (CCL) waste as a carbon precursor. Herein, for the first time, we demonstrated the preparation of biomass-derived activated carbon from CCL via KOH activation with straightforward pyrolysis procedures at high temperatures. KOH activation with straightforward pyrolysis and its effect on the physicochemical properties and electrochemical activity of the CCL electrodes were investigated. In addition, the influence of acidic and neutral electrolytes on the electrochemical activity of the sample was also explored. The CCL electrodes were prepared in a free-standing manner without any addition of adhesive material, conductive pigments, etc. More importantly, this study provides an obvious method to select suitable plant waste for sustainable development of biomass-derived activated carbon with superior performance for use as SC electrode materials.

## Material and methods

### Preparation

*Coffea canephora* leaf (CCL) waste was used as raw material for the preparation of activated carbon and was collected from Bengkulu province, Indonesia. First, the leaf was sun-dried for 12 h and then oven-dried for 48 h at 110°C. Afterward, the dried sample was pre-carbonized in at 250°C for 2.5 h and powdered. The powder was mixed into a KOH solution with different concentrations (0.1 M, 0.3 M, and 0.5 M) at 80°C for 2 h; afterward, it was oven-dried for 48 h at 110°C. The dried samples were molded into monolith form under pressure of 8 metrics tons using hydraulic press (Taer and Taslim 2018; Taer et al. 2021, 2021). Then, the monolith forms underwent straightforward pyrolysis via carbonization at 600°C under N<sub>2</sub> gas with subsequent physical activation at 850°C for 2.5 h under CO<sub>2</sub> gas atmosphere. The obtained samples were washed using distilled water until neutral pH was reached. The obtained samples were overnight dried at 110°C and denoted as CCL-0.1, CCL-0.3, and CCL-0.5.

### Material characterization

Scanning electron microscopy (SEM, JEOL-JSM 6510, Japan) along with energy-dispersive X-ray (EDX) was employed to observe the morphology and elemental contents of the CCL samples. The crystal phase structure was detected using X-ray diffraction (XRD, X-pert powder PANalytical) with light source CuK<sub>α</sub> radiation with  $\theta$  ranging between 10 and 80°. The crystal size of the as-prepared samples was obtained using the Debye-Scherrer formula (Ghosh et al. 2019; Jayachandran et al. 2021; Maher et al. 2021). The FT-IR spectrometer (IRprestige A210048, Shimadzu) was applied to explore the functional groups.

### Electrochemical measurements

To evaluate the actual electrochemical performance of the free-standing CCL samples, the symmetrical two-electrode setup was applied and was evaluated in 1 M H<sub>2</sub>SO<sub>4</sub> and 1 M Na<sub>2</sub>SO<sub>4</sub> electrolytes. The free-standing CCL electrodes were used without any adhesive materials, and conductive pigment with a diameter and thickness ranged between  $\pm 0.8$  mm and  $\pm 0.2$  mm were used as a cathode and anode, respectively. The free-standing CCL electrodes were soaked in the electrolyte solution for 48 h. Afterward, the two pieces of electrodes were sandwiched together into a coin cell consisting two stainless steel 316 L plates as current collectors. The cyclic voltammetry (CV) and galvanostatic charge/discharge (GCD) measurements were operated at the potential range of 0–1 V. The

electrochemical impedance spectroscopy (EIS) test was operated at the frequency ranges from 0.01 mHz to 100 kHz. The specific capacitance ( $C_{sp}$ ) based on CV and GCD data was calculated according to Equations (1) and (2):

$$C_{sp} = \frac{2I}{sm} \quad (1)$$

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

where  $I$  (A),  $\Delta t$  (s),  $m$  (g),  $\Delta V$  (V) are discharge current, scan rates, total mass of the electrodes, discharge time, and the voltage, respectively. The volumetric capacitance ( $C_v$ ) of the CCL samples was calculated according to the formula:

$$C_v = C_{sp}\rho \quad (3)$$

where  $C_{sp}$  is the specific capacitance ( $F\ g^{-1}$ ) and  $\rho$  is the activated carbon monolith density ( $g\ cm^{-3}$ ). The specific energy ( $E_{sp}$ ) and specific power ( $P_{sp}$ ) were calculated according to Equations (4) and (5), respectively.

$$E_{sp} = \frac{1}{2} C_{sp} V^2 \cdot \frac{1}{3.6} \quad (4)$$

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

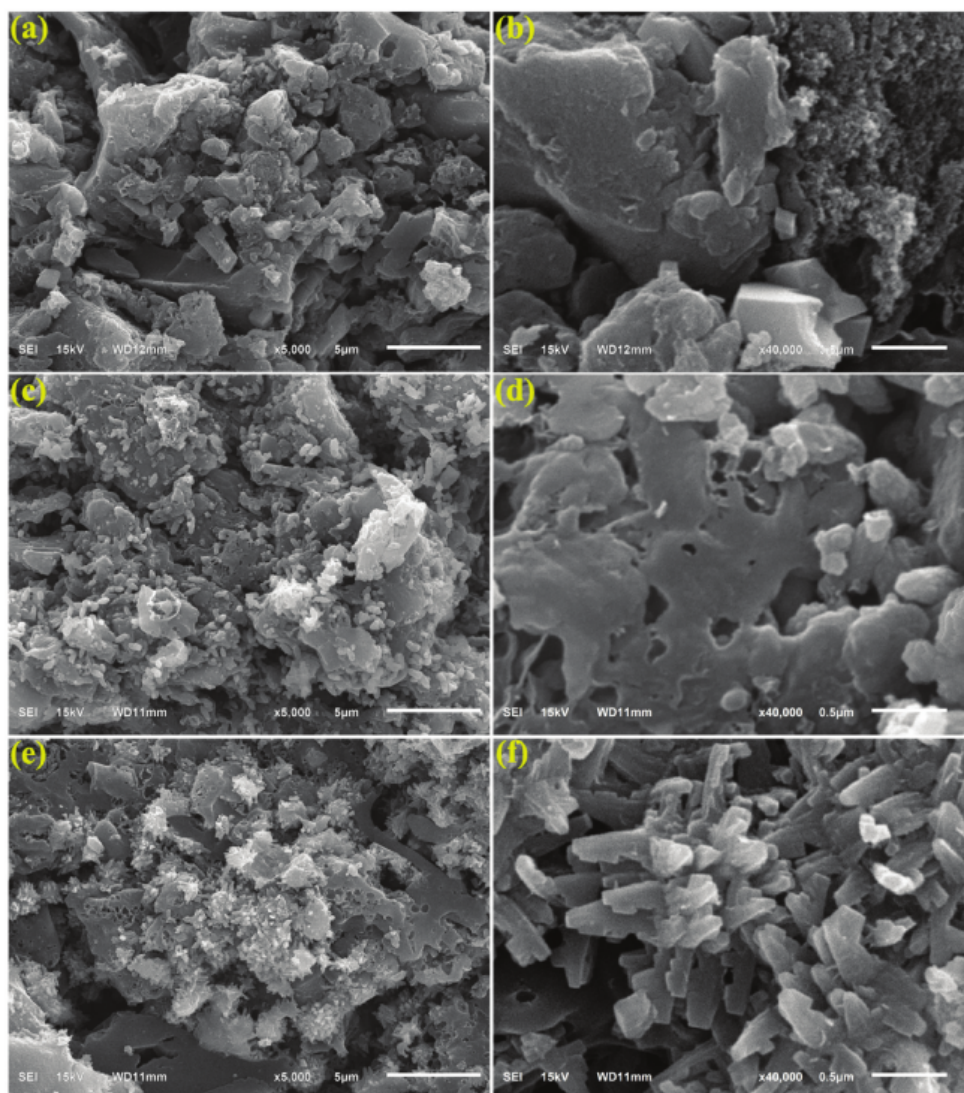
## Results and discussion

The yields of weight losses after straightforward pyrolysis processes are summarized in Table 1. The straightforward pyrolysis processes accounted for the majority of weight losses. Furthermore, the concentration of KOH is contributed to the carbon yield obtained from the percentage of mass. In the CCL samples, the highest carbon yields were found at 0.1 M KOH concentration (CCL-0.3) whereas there was the lowest carbon yields (CCL-0.1) at 0.3 M KOH concentration. The lower carbon yields on the CCL-0.3 will provide to larger specific surface area and higher porosity (Wang et al. 2021).

The details of morphological structure of CCL samples at 5000 and 40,000 magnifications are represented in Figure 1. Figure 1(a,b) displays the morphological structure of the CCL-0.1 sample. It can be observed that the CCL-0.1 sample is dominated by perforated tunnels which can be linked to volatile gasification during carbonization and activation. The particles showed non-uniformity, whereas the pores also showed different shapes and sizes. Furthermore, it can be seen that the surface morphologies of CCL-0.1 are filled with cavities and are completely irregular as a consequence of the carbonization and activation process with huge amounts of flake and micro-mesopores shaped like slits. It can be known that during the carbonization and activation, the evaporation of  $K_2CO_3$  occurs, resulting in the formation of cavities, leaving empty spaces previously occupied by  $K_2CO_3$  (Mai et al. 2019). A substantial change in morphology is seen on the CCL-0.3 sample as a result of change in KOH concentration and is displayed in Figure 1(c,d). As presented in Figure 1(c), it can be observed that the surface structure of CCL-0.3 is dominated by fine particles with a rod-like structure. However,

**Table 1.** The percentage of weight losses, and carbon yields of CCL samples.

Samples	Weight losses (%)	Carbon yields (%)
CCL-0.1	72.27	27.73
CCL-0.3	84.74	15.26
CCL-0.5	77.35	22.65



**Figure 1.** SEM image of CCL-0.1 (a and b), CCL-0.3 (c and d), and CCL-0.5 (e and f) at different magnifications.

at the higher magnification (see [Figure 1\(d\)](#)), the presence of hollow pore structures on the surface of sample can be seen. These changes in morphological on the CCL-0.3 can be attributed to the removal of volatile components from the *Coffea canephora* leaf through the decomposition of lignocellulosic. During the carbonization and activation process, the moisture from the lignin is evaporated, and the inorganic component produces volatile undergoes decomposition, resulting in the porous network. Extreme changes in the surface structure of the CCL sample are also seen at CCL-0.5 and depicted in [Figure 1\(e,f\)](#). As represented in [Figure 1\(e\)](#), it can be observed that the surface structure of CCL-0.5 consists of a large amount of fine particles with crystal-like shape and the figure also shows the presence of hollow pores on the surface of CCL-0.5. Furthermore, at the higher magnification (see [Figure 1\(F\)](#)), surface structure of CCL-0.5 shows the sheet-like structure jagged of various sizes. These structure are most likely the calcium compounds as shown by the EDS results (see [Table 1](#)) which has high calcium content in the CCL-0.1 sample (6.38 wt%).

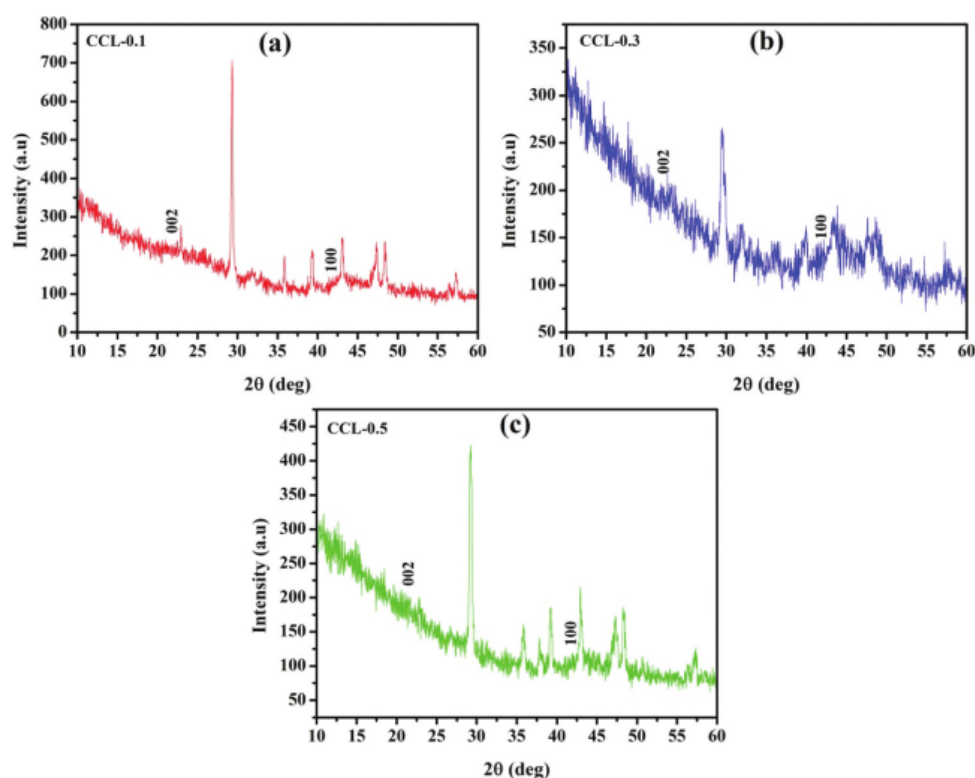
[Table 2](#) shows the EDS results of the CCL-0.1, CCL-0.3, and CCL-0.5 samples. All three samples clearly show the existence of carbon, oxygen, magnesium, calcium, and niobium, but the EDS spectra

**Table 2.** EDS results of the CCL samples.

Samples	Elements					
	C(% wt)	O(% wt)	Na(% wt)	Mg(% wt)	Ca(% wt)	Nb(% wt)
0.1 M	77.95	14.15	-	0.7	5.00	2.20
0.3 M	72.75	18.91	0.05	0.61	5.55	2.13
0.5 M	73.92	17.02	-	0.79	6.38	1.89

of the CCL-0.3 sample show the presence of the element sodium. All the CCL samples are dominated by the carbon and oxygen contents with >70 wt% and >17 wt%, respectively. The CCL-0.3 showed a higher oxygen content than the CCL-0.1 and CCL-0.5. It can be inferred that the CCL-0.3 has a good electrochemical performance. The other elements, i.e. sodium, calcium, magnesium, and niobium, most likely are inorganic elements which are naturally present in the raw materials.

To identify the crystal phase structure of the CCL samples, the XRD spectra of CCL-0.1, CCL-0.3, and CCL-0.5 are displayed in Figure 2. The primary diffraction peaks of activated carbon can be identified by the XRD spectra, which demonstrate the characteristic of amorphous features of the carbonaceous material. Two prevalent diffraction peaks at  $2\theta$  around  $22\text{--}24^\circ$  and  $42\text{--}44^\circ$  can be associated with the (002) and (100) crystal planes, respectively (Lu et al. 2018; Ma et al. 2018). Generally, in the XRD spectra of CCL-0.1, CCL-0.3, and CCL-0.5, relatively there is no difference, indicating that no graphitization occurred the increasing KOH concentration during chemical activation process. Moreover, the obtained sharp peaks of CCL-0.1, CCL-0.3, and CCL-0.5 positioned at  $2\theta$  indicated the presence of silica oxide ( $\text{SiO}_2$ ) in the samples. The sharp peaks were reduced upon the increase of KOH concentration from 0.1 M to 0.3 M that leads to the decline of crystallinity; inversely, by increasing the concentration of KOH to 0.5 M, the sharp peaks were increased on the CCL-0.5.

**Figure 2.** XRD spectra of CCL-0.1 (a), CCL-0.3 (b), and CCL-0.5 (c).

From Scherer's formula, the crystallite size of the CCL samples was obtained and shows a considerable change following the concentration of KOH. It occurs around of 0.513 nm for CCL-0.1, while it drops to 0.415 nm for CCL-0.3. While the rise of concentration into 0.5 M induced the rise of crystallite size to be 0.504 nm for CCL-0.5. The effect of KOH concentration changes toward susceptibility of regularity via lattice stacking refers to the orientation of crystallographic differentiation. The calculated of interlayer distance value ( $d_{002}$ ), the CLs samples have the higher value than graphite (3.35 Å). The CCL-0.3 has the lowest interlayer distance with 3.56 Å, whereas CCL-0.1 and CCL-0.5 have 4.07 Å and 3.67 Å, respectively.

The FTIR spectra of CCL-0.1, CCL-0.3, and CCL-0.5 are represented in Figure 3. The bands are observed at  $3454.29\text{ cm}^{-1}$ ,  $3464.01\text{ cm}^{-1}$ , and  $3473.12\text{ cm}^{-1}$  which correspond to the O-H group's (carboxyl acid) stretching vibrations. The C=C stretching vibration was observed at  $1632.62\text{ cm}^{-1}$ ,  $1645.56\text{ cm}^{-1}$  and  $1626.93\text{ cm}^{-1}$ . Furthermore, the peaks at  $1121.10\text{ cm}^{-1}$ ,  $1120.68\text{ cm}^{-1}$ , and  $1110.96\text{ cm}^{-1}$  are attributed to the existence of C-O stretching vibration.

### Electrochemical activity analysis

To explore the performance of the different free-standing CCL electrodes in  $1\text{ M H}_2\text{SO}_4$  and  $1\text{ M Na}_2\text{SO}_4$  electrolytes, cyclic voltammetry was used and applied in symmetrical two-electrode setup and are displayed in Figure 4(a,b). The CV profile of the CCL electrodes in both electrolytes has a mechanism of storage based on the creation of charge-separated state in the electric double layer before and generally have a quasi-rectangular-shaped characteristics. The larger CV area of CCL-0.3 in  $1\text{ M H}_2\text{SO}_4$  and  $1\text{ M Na}_2\text{SO}_4$  electrolytes can be observed from Figure 4(a,b), indicating that it had a higher capacitance than CCL-0.1 and CCL-0.5. The value of specific capacitances of CCL-0.1, CCL-0.3, and CCL-0.5 at  $1\text{ mV s}^{-1}$  was obtained to be  $129\text{ F g}^{-1}$ ,  $177\text{ F g}^{-1}$ , and  $139\text{ F g}^{-1}$  for  $\text{H}_2\text{SO}_4$  electrolyte,  $59\text{ F g}^{-1}$ ,  $130\text{ F g}^{-1}$ , and  $99\text{ F g}^{-1}$  for  $\text{Na}_2\text{SO}_4$  electrolyte, respectively.

Figure 4(c,d) displays the influence on the specific capacitances with the rise in scan rate for all the CCL samples in  $1\text{ M H}_2\text{SO}_4$  and  $1\text{ M Na}_2\text{SO}_4$  electrolytes, respectively. It was can be observed that CCL-0.3 possess a higher specific capacitance compared to CCL-0.1 and CCL-0.5 in both electrolytes. Moreover, as seen from Figures 4(c,d), the specific capacitance declines with rises in scan rates and vice versa. This is owing to the insufficient use of dynamic electrode active sites by ion of electrolytes with rise in scan rates (Ahmed, Ahmed, and Rafat 2018; Ahmed and Rafat 2018). Furthermore, it can be concluded that CCLs in  $1\text{ M H}_2\text{SO}_4$  have a higher specific capacitance value

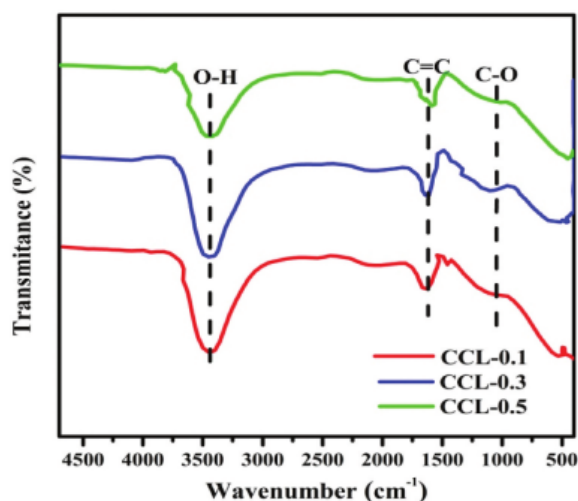
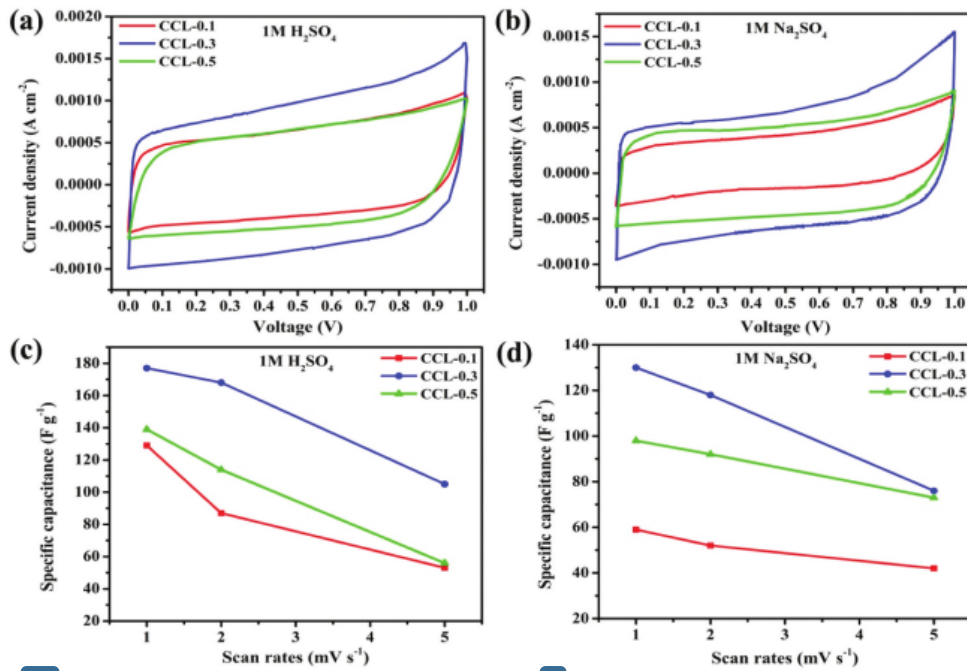


Figure 3. FTIR spectra of CCL-0.1, CCL-0.3, and CCL-0.5.





**Figure 4.** CV curve of the CCL samples (a) in 1 M H<sub>2</sub>SO<sub>4</sub> electrolyte, (b) in 1 M Na<sub>2</sub>SO<sub>4</sub> electrolyte, and specific capacitance vs. scan rates of the CCL samples, (c) in 1 M H<sub>2</sub>SO<sub>4</sub> electrolyte, and (d) in 1 M Na<sub>2</sub>SO<sub>4</sub> electrolyte.

than the CCLs in 1 M Na<sub>2</sub>SO<sub>4</sub> electrolyte. The specific capacitance of the CCL samples in 1 M H<sub>2</sub>SO<sub>4</sub> and 1 M Na<sub>2</sub>SO<sub>4</sub> electrolytes at different scan rates are mentioned in Table 3.

In order to estimate the specific capacitance of supercapacitors, the GCD study is a trustful and practical method. The GCD studies are shown for the free-standing CCL electrodes in different aqueous electrolytes and are presented in Figure 5. Figures 5(a,b) display the GCD curves of CCL-0.1, CCL-0.3, and CCL-0.5 at 1 A g<sup>-1</sup> in 1 M H<sub>2</sub>SO<sub>4</sub> and 1 M Na<sub>2</sub>SO<sub>4</sub> electrolytes, respectively. The GCD curves for all the CCL electrodes show a nearly triangular shape, demonstrating a good electrochemical stability and good ion accessibility at the interface of electrode/electrolyte, indicating the charge storage mechanism of the CCL electrodes. The specific capacitance of CCL-0.1, CCL-0.3, and CCL-0.5 were found to be 128 F g<sup>-1</sup>, 297 F g<sup>-1</sup> and 207 F g<sup>-1</sup> for H<sub>2</sub>SO<sub>4</sub> electrolyte, 67 F g<sup>-1</sup>, 220 F g<sup>-1</sup> and 191 F g<sup>-1</sup> for Na<sub>2</sub>SO<sub>4</sub> electrolyte, respectively. Furthermore, the calculated volumetric capacitance of CCL-0.1, CCL-0.3, and CCL-0.5 are 13.63 F cm<sup>-3</sup>, 20.99 F cm<sup>-3</sup>, and 20.40 F cm<sup>-3</sup> for H<sub>2</sub>SO<sub>4</sub> electrolyte, 7.13 F cm<sup>-3</sup>, 15.55 F cm<sup>-3</sup>, and 18.82 F cm<sup>-3</sup> for Na<sub>2</sub>SO<sub>4</sub> electrolyte, respectively. In both electrolyte solutions, the CCL-0.3 electrode demonstrates higher specific capacitances than the CCL-0.1 and CCL-0.5 electrodes. The higher specific capacitance of CCL-0.3 can be attributed to the higher oxygen content in the sample, as confirmed by the EDS result. In addition, the CCL-0.3 electrode in H<sub>2</sub>SO<sub>4</sub> has a better interaction with the H<sub>2</sub>SO<sub>4</sub> ions than the Na<sub>2</sub>SO<sub>4</sub> ions. It can be decided that the penetration of H<sub>2</sub>SO<sub>4</sub> ions to the inner pore of CCL-0.3 is much easier during the process of charge/discharge. The

**Table 3.** The specific capacitance of the CCL samples in 1 M H<sub>2</sub>SO<sub>4</sub> and 1 M Na<sub>2</sub>SO<sub>4</sub> electrolytes at different scan rates.

Scan rates (mV s <sup>-1</sup> )	C <sub>sp</sub> (F g <sup>-1</sup> ) in H <sub>2</sub> SO <sub>4</sub>			C <sub>sp</sub> (F g <sup>-1</sup> ) in Na <sub>2</sub> SO <sub>4</sub>		
	CCL-0.1	CCL-0.3	CCL-0.5	CCL-0.1	CCL-0.3	CCL-0.5
1	129	177	139	59	130	98
2	87	168	114	52	118	92
5	53	105	56	42	76	73

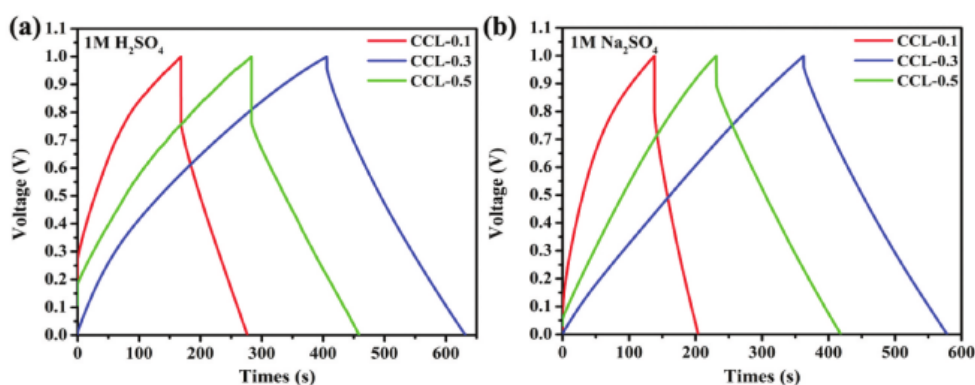


Figure 5. GCD curves of the CCL sample (a) in  $\text{H}_2\text{SO}_4$  electrolyte and (b) in  $\text{Na}_2\text{SO}_4$  electrolyte.

different hydrated radius, ionic mobility, and molar ionic conductivity in  $\text{H}_2\text{SO}_4$  and  $\text{Na}_2\text{SO}_4$  electrolytes also affected the performance of CCL-0.3.

The specific energy and specific power of the CCL samples are calculated by Equations (4) and (5). The maximum specific energy for the CCL samples is obtained on the CCL-0.3 sample for both electrolyte solutions. The specific energy of the CCL-0.3 samples is  $41.25 \text{ Wh kg}^{-1}$  at specific power of  $657.95 \text{ W kg}^{-1}$  in  $1 \text{ M H}_2\text{SO}_4$ ,  $30.56 \text{ Wh kg}^{-1}$  at specific power of  $510.28 \text{ W kg}^{-1}$  in  $1 \text{ M Na}_2\text{SO}_4$ . This value is significantly larger than the most previously reported electrode materials prepared from other biomass precursors such as kelp, water chestnut, mango seed, black tea, and pineapple leaf fibers, and are summarized in Table 4.

To estimate the conception of the interactions of between electrode/electrolyte, the EIS measurement is required to represent Nyquist plots of the CCL-0.3 electrode. The Nyquist plot ( $-Z''$  vs  $Z'$  plot) at varying frequencies of CCL-0.3 in  $1 \text{ M H}_2\text{SO}_4$  is shown in Figure 6(a). Figure 6(a) displays a Nyquist curve of CCL-0.3 using Corrtest Studio v6.0 software. In the high-frequency region, the Nyquist curve shows a semicircle, while in the low-frequency region, it shows a vertical line to demonstrate the resistance of

Table 4. Electrochemical performance of the CCL samples compared to other biomass precursors previously reported.

Carbon precursor	Electrolytes	$C_{sp}$ ( $\text{F g}^{-1}$ )	$E_{sp}$ ( $\text{Wh kg}^{-1}$ )	$P_{sp}$ ( $\text{W kg}^{-1}$ )	References
<i>Tectona grandis</i> leaf	$1 \text{ M H}_2\text{SO}_4$	168	23.19	83.56	(Taer et al. 2021)
Kenaf	$6 \text{ M KOH}$	212	6	215	(Park et al. 2021)
Sugarcane tip	$6 \text{ M KOH}$	228.3	7.93	100	(Wei et al. 2021)
<i>Sapindus trifoliatus</i> nut shells	$6 \text{ M KOH}$	240.8	30	400	(Vinayagam et al. 2021)
Pineapple leaf fiber	$1 \text{ M H}_2\text{SO}_4$	133	27	148	(Kongthong et al. 2022)
Teak leaves	$1 \text{ M H}_2\text{SO}_4$	280	9.72	70.12	(Taer et al. 2021)
<i>Terminalia cattapa</i> leaf	$1 \text{ M H}_2\text{SO}_4$	54	-	-	(Taer et al. 2018)
Tobacco waste	$6 \text{ M KOH}$	120	2.66	51	(Chen et al. 2017)
Cotton	$6 \text{ M KOH}$	270	18	250	(Zhang et al. 2018)
Cottonseed hull waste	$6 \text{ M KOH}$	346	-	-	(Jiang et al. 2020)
Cellulose carbamate	$6 \text{ M KOH}$	289	-	-	(Zhou et al. 2017)
Cottonseed hull	$6 \text{ M KOH}$	304	21.1	250	(Jiang et al. 2018)
Kelp	$6 \text{ M KOH}$	166	5.76	124.92	(Li et al. 2021)
Mango seeds	$2 \text{ M NaOH}$	135	19	1077	(Wickramaarachchi et al. 2021)
Black tea	$6 \text{ M KOH}$	482.1	19.1	325	(Zhang et al. 2021)
Wheat straw and food waste	$6 \text{ M KOH}$	81.6	11.3	240	(Liu et al. 2021)
Native European deciduous trees	$1 \text{ M H}_2\text{SO}_4$	24	0.53	51	(Jain et al. 2021)
Water chestnut shell	$6 \text{ M KOH}$	318	-	-	(Ma et al. 2022)
Zirconia-based carbon nanofiber	$6 \text{ M KOH}$	140	4.86	250	(Aydın et al. 2022)
<i>Hibiscus sabdariffa</i> fruits	$0.5 \text{ M Na}_2\text{SO}_4$	29	13.10	225	(Hamouda et al. 2020)
Pinecone	$1 \text{ M H}_2\text{SO}_4$	43	5.97	253	(Rajesh et al. 2020)
<i>Coffea canephora</i> leaf	$1 \text{ M H}_2\text{SO}_4$	297	41.25	657.95	This work
	$1 \text{ M Na}_2\text{SO}_4$	220	30.56	510.28	

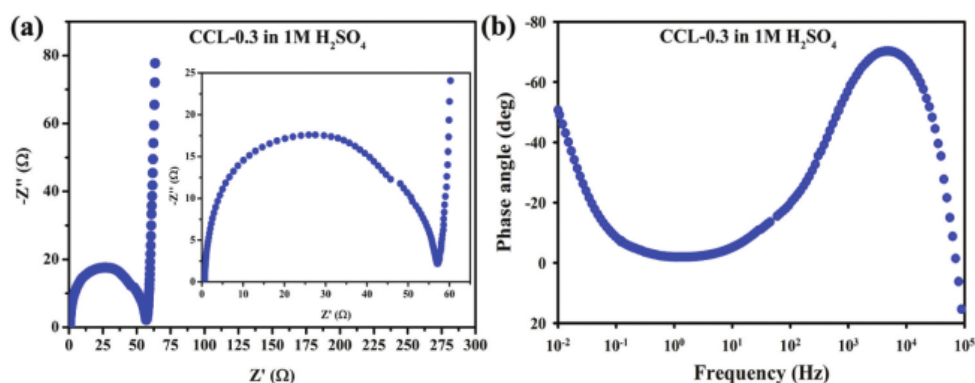


Figure 6. (a) Nyquist plot and (b) Bode phase angle plot (deg) vs. frequency (Hz) of CCL-0.3 in 1 M  $\text{H}_2\text{SO}_4$ .

charge transfer in the electrolyte ions and diffusion of them in the pore of electrodes. In particular, an increase of Warburg tails with slopes close to  $90^\circ$  at low frequencies demonstrates that the activated carbon 5 especially CCL-0.3, possesses perfectly EDLC characteristic (Senthilkumar et al. 2013; Wan et al. 2019). The equivalent series resistance ( $R_s$ ) and the charge transfer resistance ( $R_{ct}$ ) values of CCL-0.3 in 1 M  $\text{H}_2\text{SO}_4$  are  $0.73 \Omega$  and  $4.9 \Omega$ , respectively. Figure 6(b) depicts the phase angle (degree) vs. response frequency (Hz) of CCL-0.3 in 1 M  $\text{H}_2\text{SO}_4$ . Based on the Bode phase angle plot, it was clear that CCL-0.3 in 1 M  $\text{H}_2\text{SO}_4$  has phase angle at  $-50.66^\circ$  at a low frequency, around 0.01 Hz, which further confirmed the charge storage feature of double layer (Sankar and Kalai Selvan 2015; Senthilkumar et al. 2013).

## Conclusions

In summary, *Coffea canephora* leaf has been successfully prepared via chemical activation with straightforward pyrolysis procedures for the first time. KOH with different concentrations, i.e. 0.1 M, 0.3 M, and 0.5 M, were used as an activator for the chemical activation. The sample prepared using 0.3 M KOH (CCL-0.3) displayed a good physicochemical properties and exhibited a superior electrochemical performance as SC electrode materials compared to the other two samples (0.1 and 0.5 M). The symmetrical device prepared using CCL-0.3 as anode and cathode electrodes showed a superior electrochemical performance with specific capacitances of  $297 \text{ F g}^{-1}$  in 1 M  $\text{H}_2\text{SO}_4$  19 and  $220 \text{ F g}^{-1}$  in 1 M  $\text{Na}_2\text{SO}_4$  electrolytes, respectively. Furthermore, the CCL-0.3 has a maximum specific energy of  $41.25 \text{ Wh kg}^{-1}$  at specific power of  $657.95 \text{ W kg}^{-1}$  in 1 M  $\text{H}_2\text{SO}_4$ ,  $30.56 \text{ Wh kg}^{-1}$  at specific power of 43.28  $\text{W kg}^{-1}$  in 1 M  $\text{Na}_2\text{SO}_4$ , respectively. Furthermore, the CCL-0.3 electrode in 1 M  $\text{H}_2\text{SO}_4$  has the  $R_s$  and  $R_{ct}$  values of  $0.73 \Omega$  and  $4.9 \Omega$ , respectively. This study confirmed that biomass-derived activated carbon prepared from the *Coffea canephora* leaf via KOH activation with straightforward pyrolysis procedures at high temperatures shows to be a promising candidate for electrode materials for the development of SC devices.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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