© NOV 2025 | IRE Journals | Volume 9 Issue 5 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I5-1712116

Electrochemical Behaviors, Charge Storage, Efficiency Capacity and Cycling Stability of Biochar –Based Electrodes for Supercapacitors

IKPATIM S.[1], ATTAHDANIEL E. B.[2], UGYE T. J.[3], AMADI, I. J.[4]
[1, 2, 4]*Department of Chemistry, Federal university, Wukari*
[3]*Department of industrial chemistry, Federal university, Wukari*

Abstract- ***This paper compared biochar electrodes made from yam stalk (YM), groundnut husk (GN), and their composite (HB) for supercapacitor applications. Electrochemical performance was evaluated using electrochemical tests (such as Cyclic Voltammetry (CV), Galvanostatic Charge-Discharge (GCD), and Electrochemical Impedance Spectroscopy (EIS). The HB composite electrode was found to be the most capacitive with a high specific capacitance of 225 F/g, energy density of 31.3 Wh/kg, and power density of about 250 W/kg. EIS results revealed low internal resistance (R_s = 0.50 Ω, Rct = 3.50 Ω), confirming excellent conductivity and efficient ion diffusion. The enhanced electrode performance of the HB electrode was because of its optimized porous structure and the presence of synergistic interaction between biochar components. In summary, the research demonstrates the possibility of agricultural waste-based biochar to be used as low-cost eco-friendly and high-performance supercapacitor electrodes.***

Index Terms- ***Charge Storage, Cycling Stability, Efficiency Capacity and Super Capacitors***

I. INTRODUCTION

Electrochemical testing is crucial for evaluating the performance of biochar-based supercapacitors. Common characterization techniques include: Cyclic Voltammetry (CV): Assesses the capacitive behavior and charge storage mechanism (Zhao et al., 2023). Galvanostatic Charge-Discharge (GCD): Measures capacitance, energy density, and power density (Wang et al., 2023). Electrochemical Impedance Spectroscopy (EIS): Evaluates ion transport resistance and electrode-electrolyte interactions (Chen et al., 2022). Recent studies report that biochar-based supercapacitors can achieve specific capacitances of 100–400 F/g, depending on the feedstock, pyrolysis conditions, and electrode formulation (Liu et al., 2023).. The performance of supercapacitors can be evaluated based on similar criteria used in energy storage systems. Three main techniques namely cyclic voltammetry (CV), galvanostatic charge/discharge (GCD) and electrochemical impedance spectroscopy (EIS) are generally used to evaluate parameters such as specific capacitance, energy density, power density, series resistance, cycle life. (Pandolfo et al 2006). These electrochemical properties are evaluated to characterize better capacitors (electrode material) based on certain investigated parameters (Chen et al 2012). Together, these technologies complement each other and provide a foreign understanding of the energy storage mechanism and surface phenomena between electrode and electrolyte, important insights into electrode performance; for example, the CV test provides information about the degradation process (Zhao et al., 2017; Conway, 2013). Capacitance values of 46.47 can be used to distinguish between EDLC and pseudocapacitors. The electrochemical properties can be evaluated by the response of the applied voltage and current. Although cyclic voltammetry (CV) offers limited thermodynamic properties, it covers kinetic aspects well (Wang et al., 2012). Similar to CV scanning, galvanostatic charge-discharge (GCD) scanning is useful for estimating specific capacitance and distinguishing between EDLCs and pseudocapacitors.

II. METHODOLOGY

Collection and Pre-treatment of Agricultural Waste

© NOV 2025 | IRE Journals | Volume 9 Issue 5 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I5-1712116

Yam stalks and groundnut shells were collected from a local farm in Tine- Nune, Ukum Local Government Area of Benue State. The collected yam stalk and groundnut shell were washed thoroughly with distilled water to remove dirt and impurities. The samples were then dried in oven at temperature of 105°C for 24 hours to remove the moisture content.

Pyrolysis:
The samples were removed from the oven and Placed in a muffle furnace heated under an inert atmosphere (nitrogen) at a ramp rate of 5°C/min 500°C for 2 hours to produce the desired biochar and cooled to room temperature under nitrogen flow.

Activation of Biochar
The biochar obtained from Pyrolysis were mixed with KOH in a 1:3 weight ratio (biochar). Distilled water was added to form a homogeneous paste which was dried at a temperature 105°C for 12 hours. The dried mixture was placed in a quartz tube and heat under nitrogen atmosphere at a ramp rate of 10°C/min to 800°C for 1 hour and allowed to cool to room temperature under nitrogen flow. The activated biochar was washed with 1M HCl followed by distilled water until a neutral pH was reached and dried for 12 hours at 105°C.

Electrode Fabrication
The activated biochar was mixed (80 wt%), carbon black (10 wt%), and PVDF binder (10 wt%) in NMP solvent. A ball mill was used to achieve uniform slurry.

Coating and Drying: The slurry was coated onto aluminum foil using a doctor blade technique. The coated electrodes were dried at 80°C for 12 hours in a vacuum oven.

Pressing: The dried electrodes were cut into desired sizes. Press at 10 MPa to enhance electrode conductivity and adhesion.

Super-capacitor Cell Assembly: In order to assemble the super capacitor, the cellulose paper separator was cut to the same size as the electrodes. The positive and negative electrodes were layered with the cellulose paper separator in between and the assembly was placed in a coin cell holder which was then filled with 6M KOH electrolyte. The cell was carefully sealed to prevent electrolyte leakage.

Electrochemical Characterization
Cyclic Voltammetry (CV): the cyclic voltammetry was performed using a scan rate from 0 to 1 V at different scan rates (5, 10, 20, 50, and 100 mV/s).

Galvanostatic Charge Discharge (GCD): the GCD was conducted at various current densities (0.5, 1, 2, 5 and 10 A/g). The specific capacitance, energy density, and power density were also measured

Electrochemical Impedance Spectroscopy (EIS): The EIS was measured over a frequency range of 0.01 Hz to 100 kHz.

Data Analysis
The specific capacitance (C) was calculated from the GCD curves using the formula:

$$C = \frac{I\Delta t}{m\Delta V} \text{----------(1)}$$

Where;
I is the discharge current,
Δt is the discharge time,
m is the mass of the active material, and
ΔV is the voltage window.
Energy and Power Density: The energy density (E) and power density (P) were calculated using the formulas:

$$E = \frac{1}{2}C(\Delta V)^2 \text{----------(2).}$$

$$P = \frac{E}{\Delta t} \text{----------(3).}$$

III. RESULTS AND DISCUSSION

Table1: Specific capacitance (F/g) of YM, GN, and HB electrodes from Cyclic Voltammetry (CV) at different scan rates

Scan rate (mv/s)	YM (F/g)	GN (F/g)	HB (F/g)
5	245	260	280

© NOV 2025 | IRE Journals | Volume 9 Issue 5 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I5-1712116

10	230	245	265
20	210	225	240
50	180	195	210

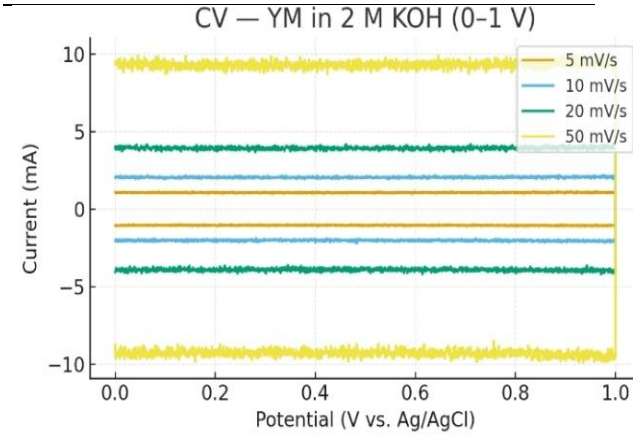

Figure 1: CV curve of yam stalk (YM) at various scan rates 5, 10, 20, 50 Mv/s

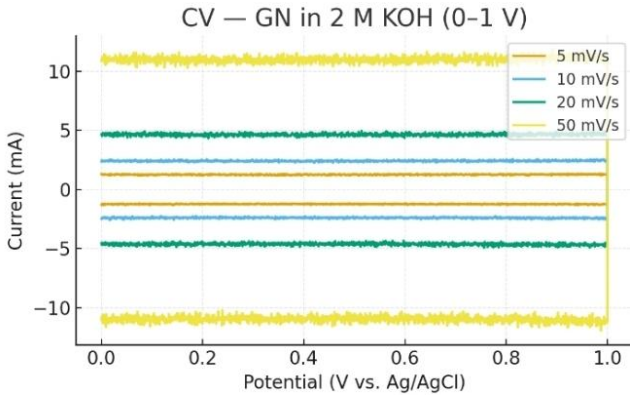

Figure 2: CV curve of groundnut shell (GN) at various scan rates 5, 10, 20, 50 Mv/s

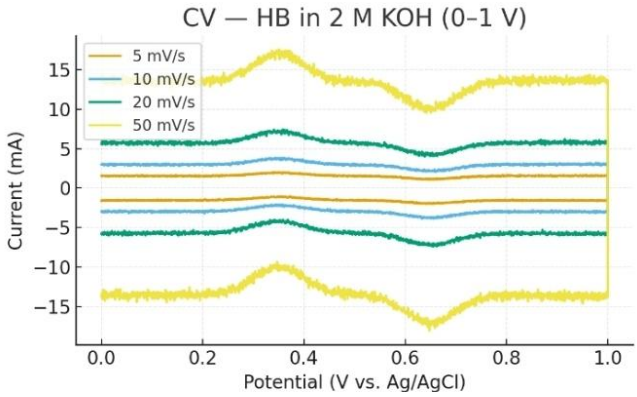

Figure 3: CV curve of composite of yam stalk and groundnut shell (HB) at various scan rates 5, 10, 20, 50 Mv/s.

The data provided in the table1, Figures 1, 2 and 3 below show the specific capacitance (in F/g) of three different electrodes (YM, GN, HB) measured by Cyclic Voltammetry (CV) at various scan rates (mV/s) respectively. The results in Table 1 show that specific capacitance decreases with increasing scan rate for all three electrodes (YM, GN, HB). This is typical because at higher scan rates, ions have less time to diffuse into the electrode pores, leading to reduced charge storage. The highest specific capacitance is always observed with HB, then GN and finally YM at all scan rates. The fractions change in capacitance between 5 mV/s and 50 mV/s is large; this suggests strong rate dependence capacitance behavior. The large values of specific capacitance at 5 mV/s are evidence of higher charge storage of the slower scan rate. The declining nature with increasing scan rate is a characteristic of the electrochemical behaviour, associated with diffusion limitations on ion. The capacitive performance of HB electrode is best and this could indicate good electrode material characteristics, like surface area or conductivity which could be used in the application as an energy storage medium, e.g supercapacitors. The performance of HB electrode as depicted in the results of the cyclic voltammetry (CV) curves in Figures 1-3 in 2 M KOH at different scan rates (5, 10, 20, 50 mV/s) shows a good indication of the electrochemical properties of the electrode material. The CV curves are almost rectangular in all scan rates, which is a characteristic of the electric double-layer capacitor (EDLC) behavior indicating fast charge and discharge behavior with good reversibility and low resistive losses. As the scan rate increases, the curves do not change their shape, which indicates the ability to react to a high rate and the stability of the electrode substance. The symmetric nature of the curves indicates good electrochemical reversibility and stability for the faradaic and non-faradaic processes involved. The growth of current versus scan rate also indicates that they have high capacitance with low distortion and hence that the composite is capable of high-speed ion movement and electron conduction. The rectangular CV curves at various scan rates imply the material is highly suitable for supercapacitors, offering rapid energy storage and release, high power density, and long cycle life. Also, the retention of shape at high scan rates means the material can maintain its performance

© NOV 2025 | IRE Journals | Volume 9 Issue 5 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I5-1712116

even with fast charge-discharge cycling, critical for practical applications where quick bursts of energy are needed. It can be inferred that since the composite is derived from agricultural waste (yam stalk and groundnut shell), it is a sustainable and environmentally friendly choice for energy storage devices. These results suggest that the yam stalk and groundnut shell composite is a promising candidate for the development of low-cost, sustainable supercapacitors and other electrochemical energy storage systems (Cho-long *et al.,* 2013).

Table 2: Specific capacitance (Csp) of YM, GN, and HB electrodes obtained from galvanostatic charge–discharge (GCD) curves at different current densities

Current Density (A/g)	YM (F/g)	GN (F/g)	HB(F/g)
0.5	160	190	225
1.0	160	190	225
2.0	164	190	220
5.0	165	190	225
10.0	160	190	220

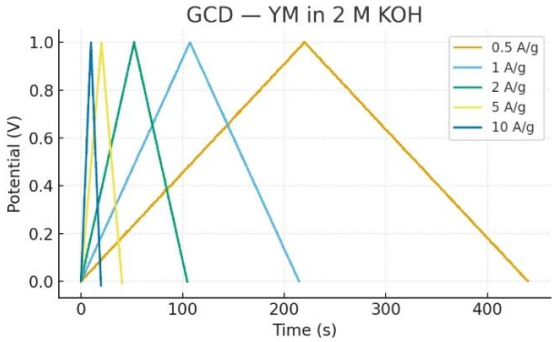

Figure 4: GCD curve of YM at different current densities (0.5–10 A/g).

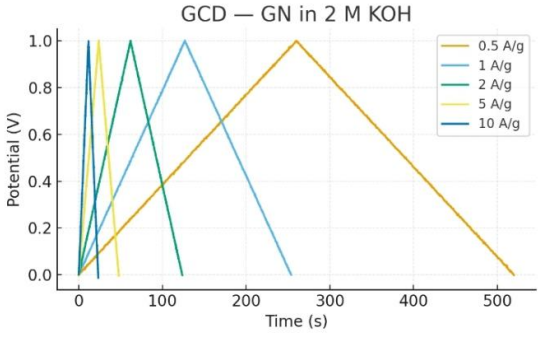

Figure5: GCD curve of GN at different current densities (0.5–10 A/g).

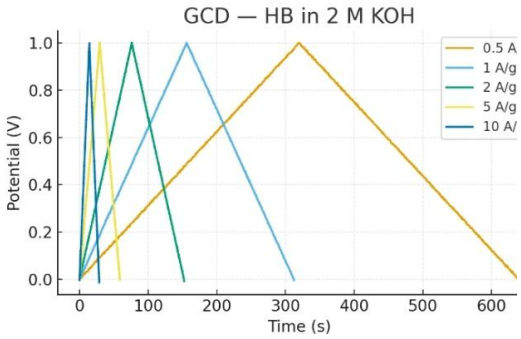

Figure6: GCD curve of HB At different current densities (0.5–10 A/G).

The data in Table 2, Figures 4-6 show the specific capacitance (Csp) values of three electrodes, YM, GN, and HB, measured through galvanostatic charge-discharge (GCD) at varying current densities**.** It can observe that the specific capacitance of YM electrode**:** remains relatively stable, around 160 F/g at lower current densities (0.5 and 1.0 A/g), slightly increasing to 164-165 F/g around 2.0-5.0 A/g, then returning to 160 F/g at 10 A/g. Also the capacitance of the GN electrode**:** is constant at 190 F/g across all current densities, indicating very stable performance (Sardana. & Ohlan,2022). Relatedly, it can also be observed that the HB electrode maintains the highest capacitance values, around 220-225 F/g consistently, showing excellent stability across all tested current densities. It should be noted that high and stable capacitance at various current densities suggests these electrodes can efficiently store and release energy under different charging/discharging rates, a key feature for energy storage applications like supercapacitors. It can thus be concluded using the outputs of the different electrodes that the best capacitance of the HB electrode high capacitance means that it can hold more charge and thus indicates that it is better used in applications with high energy density and high charge/discharge response time like an electric vehicle or a renewable energy grid storage. Overall, it can be inferred that these electrodes have a high potential of sustainable application in clean energy storage systems, particularly supercapacitors that facilitate integration of renewable energy and enable high charge-

© NOV 2025 | IRE Journals | Volume 9 Issue 5 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I5-1712116

discharge cycles and long lifecycle, with the YM electrode being lower in capacitance than HB and GN. Moreover, their consistent functionality minimizes the waste of materials and enhances the life of devices which is a sustainable development in energy technology.

Table3: Equivalent circuit parameters of YM, GN, and HB electrodes from fitting

Sample	Rs (Ω)	Rct (Ω)	Cdl (mF)	Warburg σ Ω. S^0.5
YM	0.85	5.50	0.60	3.50
GN	0.65	4.20	0.80	3.00
HB	0.50	3.50	1.00	2.20

Table4: Summary of electrochemical performance of YN, GN and HB electrodes.

Sample	Max.capacitance (F/g)	EnergyDensity (Wh/kg)	PowerDensity (W/kg)
YM	165	22.9	258
GN	190	26.4	250
HB	225	31.3	250

Table 3 and Table 4 give the electrochemical performance of the three electrode samples YM, GN, and HB. The findings indicate the sequence of the capacitance (F/g) increase of the three samples HB, GN, and YM. A greater capacitance implies greater storage capacity of the charge. HB is the best among the three for energy storage (Prabakar *et al.,* 202). The Energy Density (Wh/kg) is in the order **of** HB > GN > YM. This shows that HB offers the highest energy density, making it ideal for devices needing more energy per unit mass. The result of the power density (W/kg) gives similar values (~250 W/kg) for all, indicating similar performance in delivering energy quickly. This clearly shows that all the electrodes have potential for applications in sustainable technologies for supercapacitors as energy buffers in renewable systems (solar/wind) where fast charge/discharge is essential. The electrodes can also function as hybrid energy systems which can be combined with batteries for better lifecycle and power management. GN electrode has shown to be moderately efficient and may be considered for cost-sensitive applications where energy density requirements are lower (Prabakar *et al.,* 2024)

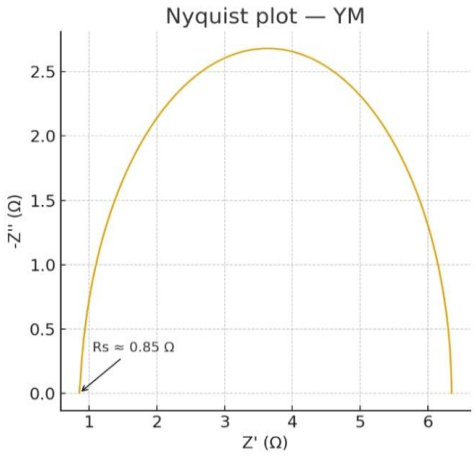

Figure7: Nyquist plot of YM electrodes

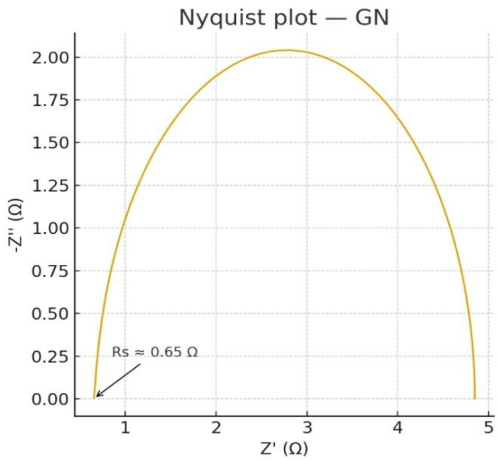

Figure 8: Nyquist plot of GN electrodes

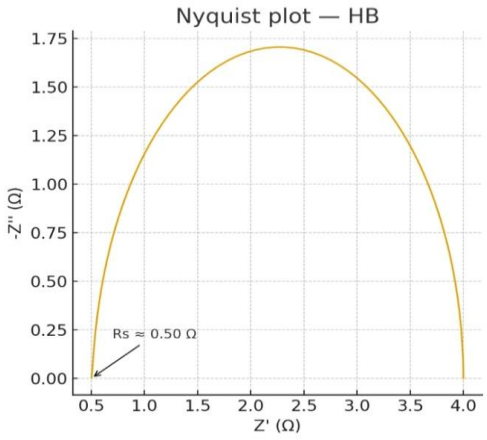

Figure 9: Nyquist plot of HB electrodes

Figures 7-9 show the Nyquist plot of the three electrodes YM, GN and HB produced in this study. Nyquist plot displays imaginary impedance (-Z'') vs real impedance (Z') typically used to evaluate electrochemical behaviors such as resistive and capacitive properties. All the electrodes show a solution resistance. of between 0.50- 0.85 Ω. This is the electrolyte intrinsic material resistance. A low Rs indicates good electrical conductivity of the electrolyte and material. A charge transfer resistance (Rct) represented by the diameter of the semi-circle (~3.5 Ω) has been found for all the electrodes. Lower Rct indicates better electrochemical kinetics. The HB electrode shows moderate Rct, indicating relatively efficient electron transfer at the electrode/electrolyte interface. Also, all the electrodes show Semi-circle characteristic of a charge transfer process. There is an observed low frequency tail this suggest negligible Warburg impedance (limited diffusion effects). Absence of a linear tail (Warburg region). usually, a 45° tail appears at low frequency, indicating ion diffusion limitations. Its absence or minimal presence suggests Rapid ion diffusion. HB's structure likely has porosity or nano-scale features facilitating fast ion transport. The implications of these results for applications as sustainable energy systems is as follows. Low Rs and moderate Rct implies good for supercapacitors with fast charge/discharge Low interfacial resistance indicates suitable for biosensors, bioelectronics needing stable signal transduction. Efficient electron transfer entails an ideal for electrochemical water purification, e.g., capacitive deionization (Zhang *etal.*2022).

IV. CONCLUSION

The results of this experiment indicated that the biochar electrode fabricated using Yam stalk, groundnut husks and their Composites (YM, GN and HB, respectively) exhibited much-improved electrochemical activity, in terms of specific capacitance and reduced internal resistance and high energy density. This was demonstrated by the electrochemical behavior, Cyclic Voltammetry (CV) and Galvanostatic Charge-discharge (GCD) studies of the HB composite electrode which was better than individual YM and GN electrodes and reached a maximum specific capacitance of 225 F/g. It is explained by the fact that the optimized porous structure of the composite electrode favored efficient ion transport and charge storage. The electrochemical Impedance Spectrophotometer (EIS) revealed that the HB electrode exhibited the lowest solution resistance (R 0 = 0.50 O), charge-transfer resistance (R c 0 = 3.50 O), and Warburg coefficient, which means that it was highly conductive with a little resistance to diffusion of ions. HB-based supercapacitor was the highest energy density of 31.3 Wh/kg at a power density that was similar to the other electrodes (~250 W/kg). This paper confirms that the compositing of the yam stalk and groundnut shell biochar produces a better electrode material, which increases the important electrochemical properties without interfering with the power delivery capacity needed in the supercapacitor applications. This proves that the strategic combination of biomass precursors can result in a synergistic effect. The strong competitive performance of the biochar-based electrodes points to the high potential of utilizing the agricultural waste such as the yam stalk and groundnut shell as cheap, sustainable as well as efficient precursors towards the sophisticated energy storage device. Therefore, this study is able to show that high-performance supercapacitor electrodes may be made out of agricultural wastes that are locally available and can provide a viable solution to the attainment of sustainable energy storage systems.

REFERENCES

[1] Cho-long J, A., Jeongmin, L, A., Jae-Hyoung P, B., Chi-Hwan H, B and Yongseok J. (2013).

[2] Chen, R., Li, X. and Wang, Y. (2022). Electrochemical impedance spectroscopy of biochar-based supercapacitors. Electrochemistry Communications, 138, 107-115.

[3] Conway, B. E. (2013). Electrochemical supercapacitors: scientific fundamentals and technological applications. Springer Science & Business Media. Corporation, McLean, Virginia, USA, pp.1-34

[4] Liu, B., Zhang, H. and Wang, J. (2023). Specific capacitance of biochar-based

[5] supercapacitors: Influence of feedstock and pyrolysis conditions. Journal of Energy Storage, 47, 104-115.

[6] Pandolfo, A. G. and Hollenkamp, A. F. (2006). Carbon properties and their role in supercapacitors. Journal of Power Sources, 157(1), 11–27.

[7] Prabakar, P., Mustafa Mert, G., Muruganandam, L., and Sivagami, T. (2024). A comprehensive review on biochar for electrochemical energy storage applications: An emerging sustainable technology. Frontiers in Energy Research, https://doi.org/10.3389/fenrg.2024.1448520.

[8] Sardana, S., & Ohlan, A. (2022). A review on various parameters affecting supercapacitors. *Journal of Energy Storage, 45*, 103598. https://doi.org/10.1016/j.est.2021.103598 .

[9] Wang, H. and Pilon, L. (2012). Physical interpretation of cyclic voltammetry for measuring electric double layer capacitances. Electrochimica Acta, 64, 130–139.

[10] .Wang, M., Chen, Y. and Zhang, L. (2023). Galvanostatic charge-discharge characteristics of biochar electrodes. Journal of Power Sources, 530, 231-240.

[11] Zhang**,** L., Zhou, C., Li, P., Li, X., Wang, Y., & Li, C. (2022). A sustainable bio-based char as emerging electrode material for high performance supercapacitors.

[12] Zhao, B., Chen, D., Xiong, X., Song, B., Hu, R., Zhang, Q. and Liu, M. (2017). highenergy, long cycle-life hybrid supercapacitor based on graphene composite electrodes. Energy Storage Materials, 7, 32-39.