

GREEN TEA BIOMASS-DERIVED CARBON MATERIAL FOR SODIUM-ION BATTERY APPLICATIONS

S Mehmood Ullah Shah^{*1}, Dr. Adnan Daud Khan², Dr. Ayesha Samreen³, Dr. Aimal Daud Khan⁴

^{*1}MS Student, Department of U.S Pakistan Center for Advanced Studies in Energy, University of Engineering and Technology Peshawar, Pakistan.

²Associate Professor, Department of U.S Pakistan Center for Advanced Studies in Energy, University of Engineering and Technology Peshawar, Pakistan.

³Lecturer, Department of Physics, University of Peshawar.

⁴PhD Scholar, Department of U.S Pakistan Center for Advanced Studies in Energy, University of Engineering and Technology Peshawar, Pakistan.

^{*1}16pwele4990@uetpeshawar.edu.pk, ²adnan.daud@uetpeshawar.edu.pk, ³ayesha.sami@uop.edu.pk

DOI: <https://doi.org/10.5281/zenodo.22250042>

Keywords

Battery Energy Storage, Green tea, hydrothermal synthesis, hydrochar, Specific capacitance; electrochemical performance.

Article History

Received: 14 July 2026

Accepted: 18 August 2026

Published: 31 August 2026

Copyright @Author

Corresponding Author: *

S Mehmood Ullah Shah

Abstract

The growing demand for sustainable and cost-effective energy storage technologies has led to the consideration of renewable biomass-derived electrode materials for sodium-ion battery applications. This work directly utilized green tea biomass as a renewable carbon precursor to prepare carbon-based electrode material via a simple hydrothermal treatment route without chemical activation or using any additional activating agents. The effect of hydrothermal reaction time was studied by preparing samples at 220 °C with 6hr, 9hr and 12hr that is GT-6, GT-9 and GT-12. The structural, elemental and surface functional properties of the obtained carbon materials were investigated by X-ray diffraction, energy dispersive X-ray spectroscopy and Fourier transform infrared spectroscopy. The electrochemical behavior was studied by cyclic voltammetry, galvanostatic charge-discharge and electrochemical impedance spectroscopy using a three-electrode cell. Out of the samples studied, the material synthesized by 12hr i.e. GT-12 of hydrothermal treatment showed best electrochemical performance with specific capacitance of 52 F g⁻¹ at current density of 1 A g⁻¹ and satisfactory impedance characteristics. The results indicate that long-term hydrothermal treatment can change the structural and surface properties of biomass-derived carbon material and enhance its charge-storage performance. To summarize, the present work demonstrates a simple, activation-free, renewable and potentially low-cost method to convert green tea biomass into a functional carbon-based electrode material for potential Sodium Ion battery applications.

1. Introduction

The rapid consumption of fossil energy and the urgent demand of sustainable development have highly promoted the worldwide efforts for exploring new technology for energy conversion

and storage. [1]Lithium-ion batteries (LIBs) dominate the commercial rechargeable battery market, thanks to their high energy density and long cycle life. [2]But the depletion and rising cost of lithium resources have driven researchers to

explore alternative battery technologies. Among the alternatives, sodium-ion batteries (SIBs) are proposed as promising candidates, due to the natural abundance, low cost and wide geographical distribution of sodium resources [3]. The development of suitable anode materials is a major challenge in sodium-ion battery technology. [4] Conventional graphite anodes used for lithium-ion batteries have poor sodium storage because of the larger ionic radius of sodium ions than lithium ions. Therefore, researchers have been concerned with the development of carbon-based materials with enhanced structural features that can efficiently host sodium ions [5]. Among the various carbon-based materials examined, biomass-derived carbons have garnered significant attention as sustainable and cost-effective precursors for the fabrication of SIB anodes. [6] Bio-mass sources are renewable, abundant and inherently rich in heteroatoms including nitrogen, oxygen and sulfur, which can improve sodium storage by providing additional active sites and improved surface wettability, compared to synthetic carbon precursors. [7]. In addition, the use of agricultural and plant-based waste for energy storage applications is consistent with broader goals of sustainable and circular use of resources. Different synthesis techniques such as pyrolysis, chemical activation and hydrothermal carbonization (HTC) have been used to convert biomass into functional carbon materials. Hydrothermal carbonization has several advantages over the other processes that include being a relatively low temperature, single step and environmentally benign process that does not require hazardous activating agents or high temperature pyrolysis and thus is economically and environmentally favorable. HTC-derived carbons are generally characterized by a disordered, amorphous structure with numerous surface functional groups that are favorable for sodium-ion insertion and storage mechanisms [8]. Green tea, a common natural product, produces a significant amount of biomass waste and is abundant in polyphenolic compounds, cellulose, and lignin, thus serving as a promising precursor for the fabrication of carbon-based

electrode materials. [9] Despite the increasing interest in biomass-derived carbons for energy storage applications, only limited research has explored the single-step hydrothermal carbonization of green tea biomass (without any additional chemical activation or pyrolysis) for sodium-ion battery anode applications. This is a big research gap, because most of the existing studies require additional activation or high temperature treatment steps to achieve good electrochemical performance, which increases the process complexity and cost. [8, 10] The green tea biomass-derived carbon (hydrochar) was synthesized by a single-step hydrothermal method at different reaction durations without using any activating agents or pyrolysis. The present work aims to investigate the structural, morphological and electrochemical properties of the prepared carbon material and to evaluate its potential as a low cost and sustainable anode material for sodium-ion battery applications.

2. Materials and Methods

2.1. Hydrothermal Synthesis of Green Tea-Derived Carbonaceous Material

Green tea biomass (200 g) was sourced from Fauji Chai, Peshawar, Pakistan and was employed as the precursor material. The biomass was divided into three portions (5 g each) to prepare samples with different hydrothermal treatment times. [11] The green tea biomass was washed thoroughly with deionized (DI) water to remove soluble components and adhering impurities and dried thereafter.

For each synthesis, 5 g of green tea biomass was dispersed in 50 mL of DI water and stirred magnetically to obtain a homogeneous suspension. The suspension was transferred into a Teflon-lined stainless steel autoclave. [12] The autoclave was sealed and held at 220 °C for 6, 9 and 12 hr. The obtained samples were designated as GT-6, GT-9 and GT-12, respectively. Figure 1 [13] after the hydrothermal treatment was completed, the autoclave was cooled down to room temperature. The suspension was then centrifuged to separate the carbonaceous material from the liquid phase. [14] The separated material

was washed with ethanol and dried for further characterization and electrode fabrication.



Figure 1. Hydrothermal synthesis of green tea biomass derived carbon material

2.2. Material Characterization

X-ray diffraction (XRD), energy-dispersive X-ray spectroscopy (EDX) and Fourier-transform infrared spectroscopy (FTIR) were used to characterize the synthesized carbonaceous materials obtained from green tea. The structural properties of the synthesized carbonaceous materials were studied by XRD analysis. The elemental composition was analyzed using EDX and the characteristic functional groups present in the materials were identified by FTIR analysis.

2.3. Preparation and Assembly of the Electrodes

The synthesized carbonaceous material was used as an active electrode material. The active material, the carbon black and the polyvinylidene fluoride (PVDF) were mixed with a mass ratio of 80:10:10, respectively. The mixture was slowly added with N-methyl-2-pyrrolidone (NMP) and fully homogenized to obtain a uniform electrode slurry. [15, 16]

Nickel foam was used as current collector. [17] The prepared slurry was uniformly coated on the nickel foam with an active geometric area of 1 cm^2 . [18] The coated electrodes were then dried to remove the NMP solvent. The loading of active material was kept at 2 mg cm^{-2} . [19]

2.4. Electrochemical Measurements

The electrochemical performance of the prepared green tea derived carbonaceous material electrodes was evaluated using a three-electrode configuration at the USPCAS-E, University of Engineering and Technology Peshawar, Pakistan. Electrochemical measurements were carried out by a Gamry Interface 1010 potentiostat/galvanostat (Gamry Instruments, USA). The working electrode was fabricated by depositing carbonaceous material on the nickel foam. [20] A Pt wire served as the counter electrode, and an Ag/AgCl electrode was used as the reference electrode. [21] [22] The electrolyte was a 1 M aqueous Na_2SO_4 solution. [23] The three-electrode configuration was employed for cyclic voltammetry (CV), galvanostatic charge-discharge (GCD) and electrochemical impedance spectroscopy (EIS) measurements. The prepared electrodes were characterized with CV measurements at different scan rates to investigate the charge-storage behavior and rate capability. The charge-discharge characteristics and specific capacitance were studied by performing GCD measurements at selected current densities. The electrochemical resistance and interfacial charge-transfer behavior of the electrodes were studied by EIS measurements. [24]

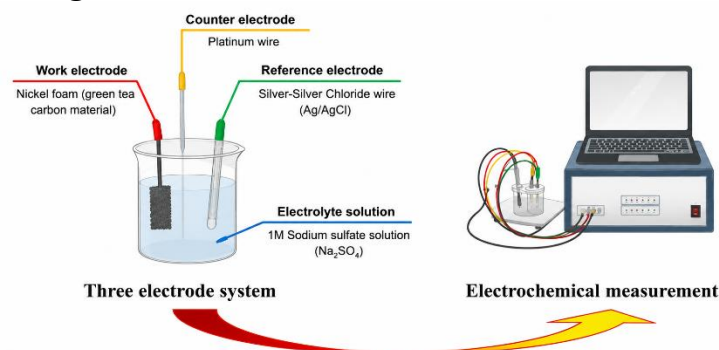


Figure 2 Electrochemical Testing

The specific capacitance of the individual working electrode was calculated from galvanostatic discharge curve by using following equation.

$$C_s = \frac{I \Delta t}{m \Delta v}$$

Where (C_s) is the specific capacitance (F/g), (I) is the discharge current (A), (t) is the discharge time (s), (m) is the mass of the active material loaded on the working electrode (g) and (v) is the potential window (V) during the discharge process.

3. Results and Discussions

3.1 XRD (X-ray Diffraction) Analysis

The structural features of the hydrochar samples (GT-6, GT-9 and GT-12) derived from green tea were investigated by X-ray diffraction (XRD, Cu $K\alpha$, $\lambda = 1.5406 \text{ \AA}$) in the 2θ range of 5° – 100° , and the patterns are presented in Figure 3.

In all three samples a broad diffraction feature is observed at $2\theta \approx 21.4^\circ$ – 21.6° , consistent with the (002) reflection of a turbostratic carbon scaffold, and a small sharp secondary feature at $2\theta \approx 15^\circ$ [7, 25]. No other peaks due to impurity or secondary crystalline phases are observed in all three patterns confirming that all three hydrochar samples were obtained as phase pure carbon materials and are free of any residual precursor salts or unwanted byproduct phases. [26]

The corresponding interlayer d-spacing were calculated to be $4.13 \text{ \AA}$ (GT-12), $4.15 \text{ \AA}$ (GT-9), and $4.14 \text{ \AA}$ (GT-6) using Bragg's law, which are substantially expanded compared to the d-spacing

of $3.35 \text{ \AA}$ for crystalline graphite [27] and even wider than the d-spacing of $3.78 \text{ \AA}$ for analogous oxidation-modified biomass hard carbon [28]. The broad (002) reflection is the well-known structural signature of turbostratic, short-range-ordered carbon produced by hydrothermal carbonization of biomass precursors [7, 25], and its expanded interlayer spacing is widely considered a key structural requirement for sodium-ion storage: unlike the tightly ordered graphite lattice, which is too narrow to reversibly accommodate the larger Na^+ ion, [29] the disordered, expanded galleries observed here provide accessible pathways for Na^+ insertion, extraction, and surface adsorption [28]. The lack of competing crystalline domains also guarantees that the whole carbon framework in each sample contributes to charge storage. [26] All three samples show this favorable turbostratic signature, but the degree of local structural ordering varies systematically across the series: • The feature (002) ($2\theta = 21.5^\circ$) is the sharpest and most intense for GT-12, which represents the highest level of short-range graphitic-type ordering and hence the most efficient electronic conduction pathway in the three samples. [25] • GT-9 displays an intermediate ($2\theta = 21.4^\circ$) peak profile, suggesting a balanced structure with moderate graphitic ordering as well as a significant density of disordered regions with defects. • GT-6 shows the broadest and least intense (002) feature ($2\theta = 21.45^\circ$) which is consistent with the most disordered framework and the highest density of active/defect sites for ion storage. The XRD data collectively confirm that the green

tea-derived hydrothermal synthetic route reliably produces phase-pure, turbostratic carbon with interlayer spacing expansion beyond that reported in the literature for similar systems [7, 28] for a

tunable GT-6–GT-12 series, thus making these hydrochar materials promising structural candidates for sodium-ion storage applications.

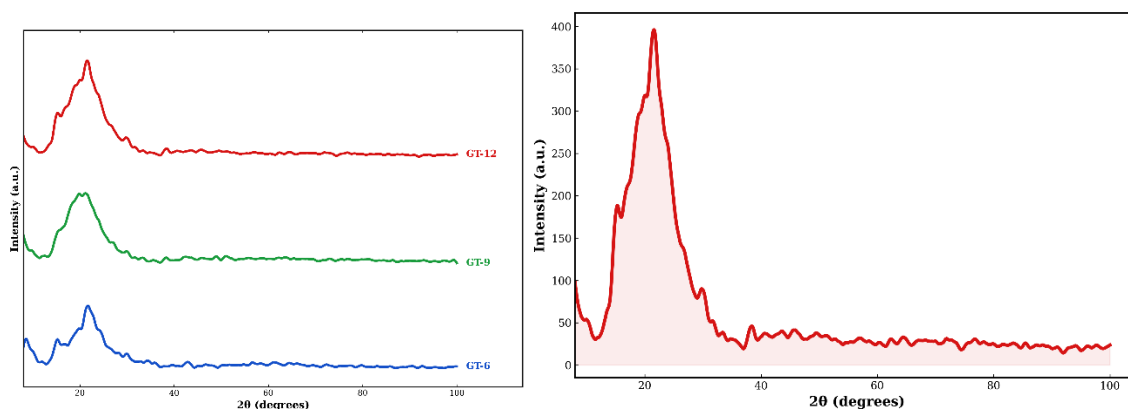


Figure 3: XRD Analysis of All Samples GT-6 GT-9 and GT-12

3.2 Morphological and Elemental Analysis (SEM-EDX)

Scanning electron microscopy (SEM) [30] was used for the characterization of the surface morphology of green tea carbon samples obtained from HTC, and their elemental composition was analyzed by energy-dispersive X-ray spectroscopy (EDX). Fig. 4(a–c) shows the SEM micrographs and the corresponding EDX spectra and quantitative elemental composition for the GT-6, GT-9 and GT-12 samples, respectively. SEM images indicate an irregular agglomerated morphology representative of hydrothermally carbonized biomass, characterized with more defined and particulate surface texture with increasing HTC duration.[32, 33] The EDX spectra confirm that carbon (C) and oxygen (O) are the dominant elements in all three samples, consistent with a carbon-rich material derived

from a cellulosic/lignocellulose biomass precursor without any metal or heteroatom doping.[34]

The quantitative analysis showed that the carbon content increased from 57.80 wt% (64.60 at%) for the 6 h sample to 59.40 wt% (66.09 at%) for the 9 h sample, and 63.97 wt% (70.29 at%) for the 12 h sample, whereas the oxygen content decreased correspondingly from 42.20 wt% to 40.60 wt% and 36.03 wt%. The increase of carbon content (and decrease of oxygen content) with the increase of HTC duration indicates the enhanced dehydration and decarboxylation reactions during hydrothermal carbonization, leading to the more carbon-enriched and less oxygenated structure at the longer treatment time.[35] This trend is in line with the superior electrochemical performance observed for the 12 h sample, corroborating the conclusion that prolonged HTC duration promotes a more carbonized, electrochemically favorable materials.[36]

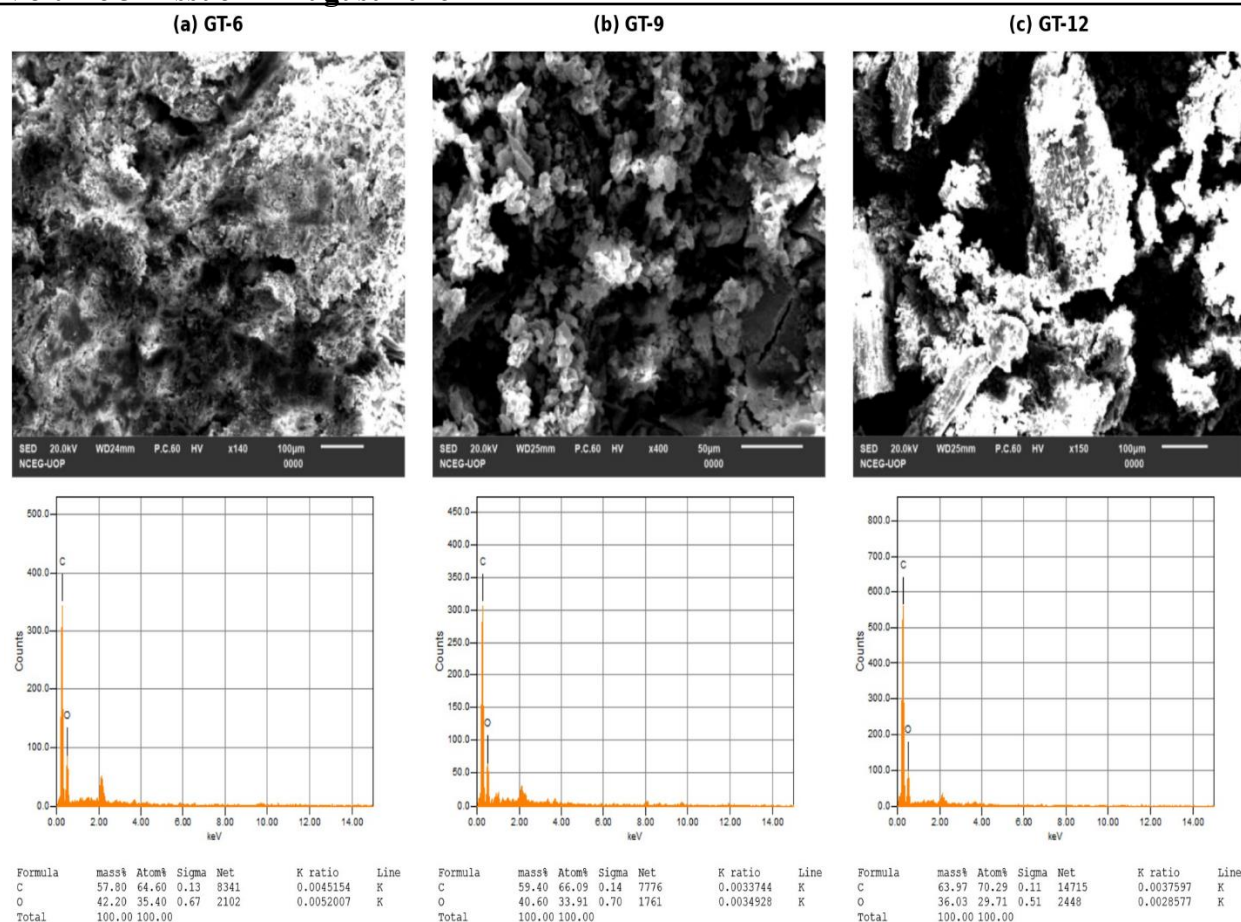


Figure 4: SEM micrographs and corresponding EDX spectra with elemental composition tables for HTC-derived green tea carbon samples: (a) GT-6, (b) GT-9, and (c) GT-12

3.2.1 Pore Development with HTC Duration

The SEM micrographs show a progressive development of porosity with increasing HTC time, as can be seen from the highlighted areas in Fig. 5. The GT-6 sample shows a relatively compact, fused morphology with only scattered, poorly developed dark cavities. [37]. The GT-9 sample shows a more granular particulate structure with visible inter-particle voids. The GT-12 sample shows the most open morphology with

large, interconnected macro pore channels separating irregular carbon fragments. The progressive increase in porosity with HTC duration is in agreement with the improved charge-transfer kinetics (lower R_{ct}) and higher specific capacitance observed for the GT-12 sample, as a more porous structure provides greater electrolyte accessibility and shorter ion-diffusion pathways.[38]

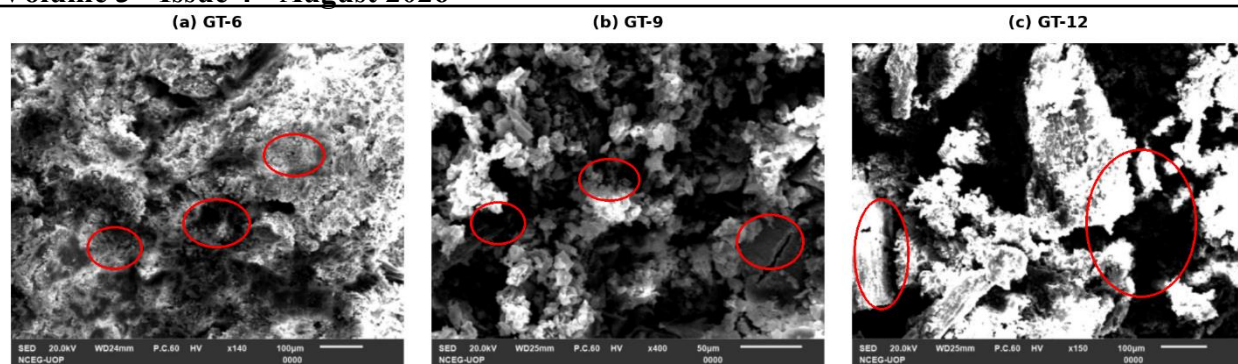


Fig: 5 Pore development with treatment time

3.2.2 Summary of Elemental Composition (EDX)

Table 1: Elemental composition of GT-6, GT-9 and GT-12 samples

Sample	C (wt%)	C (at%)	O (wt%)	O (at%)
GT-6	57.80	64.60	42.20	35.40
GT-9	59.40	66.09	40.60	33.91
GT-12	63.97	70.29	36.03	29.71

3.3 FTIR Analysis of Green Tea-Derived Carbonaceous Materials at Different Hydrothermal Treatment Duration

Figure 6 presents the FTIR spectra of the green tea derived carbonaceous materials prepared at the hydrothermal treatment times of 6, 9 and 12 hr (GT-6, GT-9 and GT-12) that is hydrochar. The spectra were recorded in the $4000\text{--}500\text{ cm}^{-1}$ range in an effort to identify the main surface functional groups and to evaluate the chemical modifications taking place with increasing hydrothermal treatment time. The spectra show characteristic bands of hydroxyl, aliphatic, carbonyl, aromatic/conjugated and oxygen containing functional groups. [39]

A broad absorption band is observed for GT-6 at about 3338 cm^{-1} due to O-H stretching vibrations of hydroxyl and hydrogen bonded surface groups. A similar band at ca. 3280 cm^{-1} was observed in GT-12, indicating that the hydrogen-bonding environment and surface hydroxyl functionality are modified with increasing hydrothermal treatment time. Broad O-H bands at about $3300\text{--}3400\text{ cm}^{-1}$ are similarly often reported for hydrochars from biomass [40]

The bands at 2920 cm^{-1} and 2850 cm^{-1} , present in all the three samples, are assigned to the stretching vibrations of aliphatic C-H groups. The relatively stable locations suggest that the aliphatic carbon-containing structures are still present after hydrothermal treatment. Similar bands in the $2849\text{--}2927\text{ cm}^{-1}$ region have been reported for biomass derived hydrochars. [41, 42]

A separate carbonyl related band occurs in the $1700\text{--}1740\text{ cm}^{-1}$ region. GT-6 shows a band at about 1703 cm^{-1} , GT-9 has features at about 1743 and 1703 cm^{-1} and GT-12 has a band at about 1730 cm^{-1} . These absorptions can be assigned to C=O stretching vibrations of oxygen containing functionalities such as carbonyl, carboxyl or ester group. Bands around 1700 cm^{-1} are characteristic of oxygenated groups preserved in hydrothermal carbonization products. [40]

The absorption band in the $1600\text{--}1620\text{ cm}^{-1}$ region is seen at $\sim 1620\text{ cm}^{-1}$ for GT-6, 1617 cm^{-1} for GT-9 and 1605 cm^{-1} for GT-12. This region may be attributed to C=C stretching of conjugated/aromatic structures, though other oxygenated functionalities may contribute to this region. A progressive shift toward lower

wavenumber with increasing treatment time suggests a modification of the carbonaceous framework during the hydrothermal conversion. Similar bands in the range of $1600\text{--}1606\text{ cm}^{-1}$ are reported for hydrochars and are associated with aromatic/conjugated carbon structures. [43]

The bands recorded at around 1450 cm^{-1} in all the samples are mainly due to C-H deformation and aromatic skeletal vibrations. The bands seen around $1100\text{--}1050\text{ cm}^{-1}$ in the low wavenumber “fingerprint” region are primarily assigned to C-O stretching vibrations. These oxygen-containing functionalities are consistent with the hydrothermal conversion of biomass, where dehydration, hydrolysis, condensation and aromatization reactions are progressively changing the original biomass structure.[43]

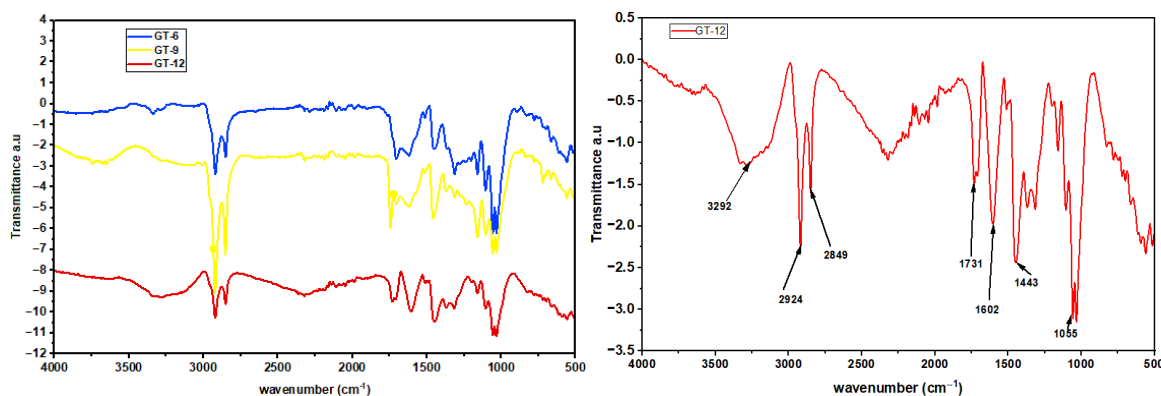


Figure 6: FTIR spectrum of GT-6, GT-9, and GT-12.

3.4. Cyclic Voltammetry Analysis

The electrochemical behavior of the GT-12 electrode was investigated by cyclic voltammetry (CV) at different scan rates in the selected potential window and the area increases with increasing scan rates as shown in Figure 7. The CV profiles show a capacitive charge storage behavior and the current response increases with the increase in the scan rate. The overall CV response indicates good electrochemical activity and efficient charge storage in the studied scan-rate range.[45] The observed electrochemical behavior was further supported by the FTIR results. Surface functionalities such as O-H, C=O, C=C/conjugated and C-O may improve the interaction between the carbonaceous surface and

The FTIR data generally confirm that hydrothermal treatment led to the formation of a carbonaceous material with both carbon-rich/conjugated structures and oxygen-containing surface functionalities. The extension of the treatment time from 6hr to 12hr led mainly to shifts and changes in the intensity of the O-H, C=O and C=C-related bands, rather than total disappearance of these functionalities. The retention of oxygen-containing groups and the formation of conjugated carbon structures are relevant to electrochemical behavior of the synthesized material, since the surface functionalities can influence the electrolyte interaction and the surface charge storage processes. [44]

electrolyte ions. These oxygen-containing functional groups can improve the surface wettability and offer electrochemically active sites, which helps to accelerate the charge storage process. Similar contributions of the surface oxygen functionalities to the electrochemical performance of biomass-derived carbon materials have been reported in the literature [19, 20]. [45, 46] Generally, the GT-12 carbonaceous material has good capacitive charge storage properties and that can be related to its carbonaceous framework and oxygen-containing surface functionalities. These features indicate the potential of hydrothermally synthesized green tea carbonaceous material for electrochemical storage application.[47]

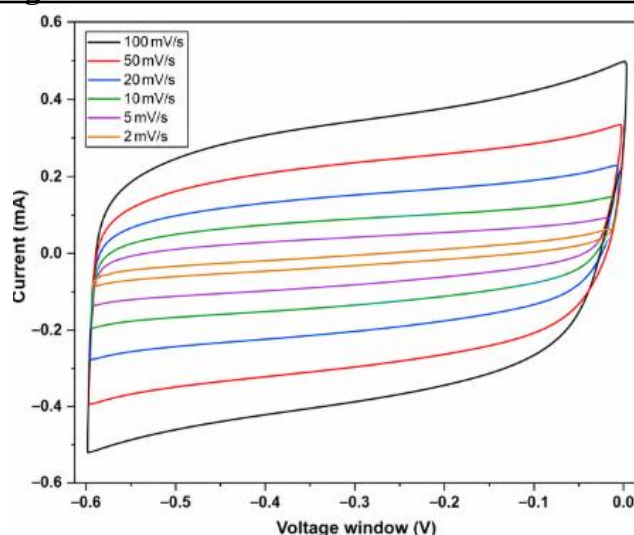


Figure 7: Scan rate of GT-12 Sample

3.5. Galvanostatic Charge–Discharge (GCD) Analysis

The galvanostatic charge–discharge (GCD) measurements of the green tea-derived carbonaceous electrodes, GT-6, GT-9 and GT-12 were carried out at a current density of 1 A g^{-1} with a mass of active material of 2 mg in the potential window from about -0.6 to 0 V . [48] The corresponding GCD profiles are shown in Figure 8. The charge-discharge profiles show the reversible charge-storage ability of the prepared carbonaceous electrodes. GCD analysis is a common method for assessing the capacitive properties and charge-storage performance of biomass-derived carbon electrodes. [49] As the hydrothermal treatment time increases, the discharge time increases. The GT-6 has a shorter discharge time, while the GT-9 and GT-12 have longer discharge durations. Higher duration of discharge for GT-12 indicates higher charge-storage capability as compared to GT-6 and GT-9. The corresponding experimental potential-time profiles are obtained directly from the GCD measurements. The progressive rise in specific capacitance with hydrothermal treatment time indicates that longer hydrothermal processing

makes favorable modifications to the carbonaceous material and leads to a higher availability of electrochemically active sites. [50, 51] The enhanced performance of GT-12 can also be ascribed to its surface chemistry. FTIR analysis confirmed the presence of oxygen containing functional groups. Such surface functionalities increase the electrolyte wettability and interaction with the carbon surface, and the carbon framework provides sites for electric double-layer charge storage. Recent research highlights the synergistic effects of surface functionalities, pore structure, ion transport, and carbon architecture on the electrochemical performance of biomass-derived carbon electrodes. [52] The GCD results generally indicate that the charge-storage performance of green tea-derived carbonaceous material is enhanced with the increase of the hydrothermal treatment time from 6 to 12 h, and GT-12 displays the maximum specific capacitance of 52 F g^{-1} at 1 A g^{-1} among the samples studied. This result indicates that the time of the hydrothermal treatment is an important parameter to tune the electrochemical properties of the green tea derived carbonaceous material.

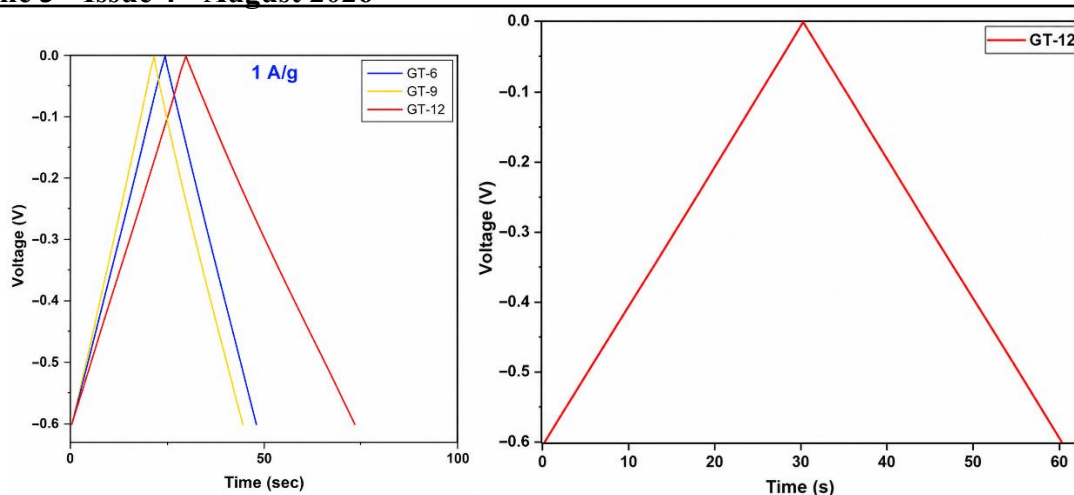


Figure 8: GCD GT-12 GT-9 GT-6

Table 2: Summary of key properties and performance metrics for various biomass-derived electrode materials.

Carbon Precursor	Activation	C_s (F/g)	Electrolyte	Ref.
Spruce Derived Biochar	No	35	1 M NaCl	[69]
Bamboo-cellulose fiber	No	43	1 M KOH	[70]
Wood biochar	No	30	2 M Li_2SO_4	[71]
Coffee Ground	Yes, KOH	105	2 M KOH	[72]
Fungus Bran	Yes, KMnO_4	150	6 M KOH	[73]
Green tea Derived Biomass	No	52	1 M Na_2SO_4	This work

3.6 Electrochemical Impedance Spectroscopy (EIS)

Electrochemical impedance spectroscopy (EIS) was employed to investigate the electrochemical behavior, internal resistance and interface properties of the green-tea-biomass-derived carbon electrodes prepared at various hydrothermal treatment times. EIS is particularly useful in discriminating the ohmic resistance of the electrochemical cell from the interfacial charge transfer processes and the ion transport behavior within the porous electrode. The electrochemical response of the biomass-derived porous carbon electrodes is determined by the pore structure, surface characteristics, conductivity, and accessibility of electrolyte ions. [53-55] The EIS measurements were analyzed using Nyquist plots,

where the real part of impedance (Z') is plotted versus the negative imaginary part ($-Z''$). The high frequency part of the Nyquist plot is normally related to the series or ohmic resistance (R_s) which comprises the electrolyte, electrode material, current collector and electrical contacts. The semicircular response in the intermediate-frequency region is related to the charge-transfer resistance (R_{ct}) and interfacial capacitive behavior. The information about ion diffusion and capacitive characteristics of the porous electrode is obtained from the low-frequency region. [56, 57] The experimental EIS data were fitted by an equivalent electrical circuit for the quantitative evaluation of impedance response. The circuit includes resistive and capacitive elements to account for the different electrochemical

phenomena at the electrode/electrolyte interface. Especially, R_s is the ohmic resistance of the electrochemical system and R_{ct} is the resistance related to the charge transfer at the electrode/electrolyte interface. Carbon electrodes are often porous and heterogeneous and their capacitive behavior is usually modeled as a constant phase element (CPE) rather than an ideal capacitor. This non-ideal behavior can be due to surface roughness, heterogeneous active sites and a distribution of pore sizes in biomass-derived carbon materials. The effect of treatment time on the electrical resistance and interfacial charge transfer characteristics was studied by comparing the EIS response of the prepared electrodes for different hydrothermal treatment durations of GT-6, GT-9 and GT-12. This comparison is especially relevant as the physicochemical properties of biomass-derived porous carbons are highly dependent on the synthesis conditions and changes in structure, porosity and surface properties can directly affect the ion transport and electrochemical performance.

3.6.1 Nyquist Plot and Equivalent Circuit Analysis

The Nyquist plot of the GT-12 hydrothermally treated green-tea-biomass-derived carbon electrode exhibits a characteristic impedance response with a broad, depressed semicircular feature in high-to-intermediate frequency region. [58, 59] The experimental impedance data (black squares) are well fitted to the response (red circles), indicating that the selected equivalent-circuit model is a good representation of the electrochemical processes at the electrode/electrolyte interface. The Nyquist plots show that the high frequency intercept on the real impedance axis is mainly attributed to the series/ohmic resistance (R_s), [60] and the semicircle corresponds to the interfacial charge-transfer resistance (R_{ct}). These Nyquist features are commonly reported for porous biomass-derived carbon electrodes and serve as tools to evaluate their electrical and interfacial electrochemical properties. [61]

The semicircular shape observed for the GT-12 electrode in a depressed manner indicates that the

electrochemical interface of this electrode is not a perfect capacitor. [62] This non-ideal behavior is usually related to the surface heterogeneity, electrode roughness, pore size distribution and non-uniform electrode/electrolyte interface. [63] So, a constant phase element (CPE) is employed in the equivalent circuit rather than an ideal capacitor to model the capacitive response of the porous biomass-derived carbon electrode in a more realistic manner. [64] Recent reviews and studies of porous carbons derived from biomass also use equivalent circuits based on CPE to describe deviations from ideal capacitive behavior. [65]

The fitted equivalent-circuit parameters of the electrodes studied also indicate that the hydrothermal treatment time enhances the interfacial charge-transfer process. The R_{ct} varies from 8.45 Ω for GT-6 to 5.36 Ω for GT-9 and 3.65 Ω for GT-12. The lowest R_{ct} obtained for the GT-12 electrode suggests a relatively lower resistance for charge transfer at the electrode/electrolyte interface. Similar EIS studies on biomass-derived porous carbons have correlated a smaller semicircle and lower R_{ct} to more favorable charge-transfer kinetics. [66]

The fitted value of R_s for the GT-12 electrode is 1.32 Ω , which is the ohmic/series resistance of the electrolyte, electrode components, current collector and electrical contacts. The R_s of the GT-12 sample is not the lowest among the three samples, but R_s is still relatively low and close to that of the GT-9 electrode (1.36 Ω). However, the remarkable decrease of R_{ct} from 8.45 Ω to 3.65 Ω implies that the large enhancement brought by the prolonged hydrothermal treatment is associated with the electrode/electrolyte interfacial charge transfer process rather than with a large reduction of the bulk ohmic resistance. The good agreement between the measured and fitted impedance spectra is further demonstrated by the coefficient of determination ($R^2=0.998$) of the GT-12 electrode. [67] This value indicates that the selected equivalent-circuit model well reproduces the experimental impedance response, allowing confidence in the extracted R_s , R_{ct} and CPE parameters. Overall, the Nyquist analysis

reveals that the interfacial impedance characteristics of the GT-12 hydrothermal treatment are the most desirable, mainly due to the greatly reduced R_{ct} and enhanced fitting quality. This behavior is in line with the

significance of electrode architecture, pore accessibility, and electrode/electrolyte interactions in governing the electrochemical performance of biomass-derived porous carbon materials. [67, 68]

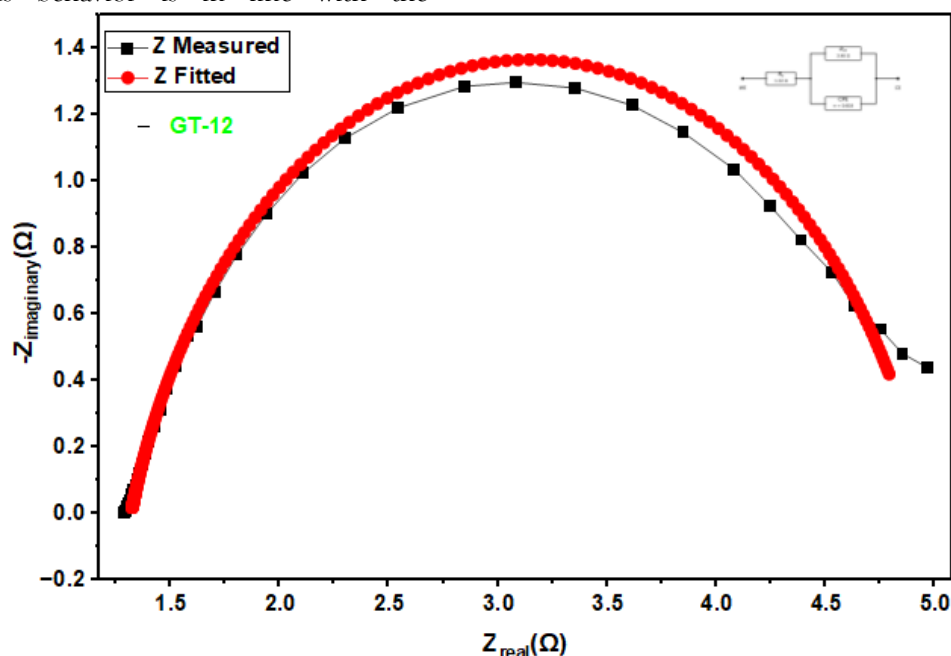


Figure 9: Nyquist Plot of GT-12

Table 3: Comparison of GT-12, GT-9 and GT-6 Samples for EIS

Sample	R_s (Ω)	R_{ct} (Ω)	CPE n	R^2
GT-6	1.08	8.45	0.766	0.955
GT-9	1.36	5.36	0.781	0.971
GT-12	1.32	3.65	0.818	0.998

As shown in Table 3, the EIS fitted parameters exhibit a different variation trend of electrochemical resistance and interfaces characteristics of the electrodes with the hydrothermal treatment duration increasing. The R_s values were 1.08, 1.36 and 1.32 Ω for the GT-6, GT-9 and GT-12 samples accordingly whereas the R_{ct} values reduced from 8.45 Ω for GT-6 to 5.36 Ω for GT-9 and 3.65 Ω for GT-12. The CPE exponent grew from 0.766 to 0.781 and 0.818 showing a slow change toward optimal capacitive behavior. Moreover, the quality of fit was greatly enhanced with R^2 increased from 0.955 for GT-6

to 0.971 for GT-9 and 0.998 for GT-12. These results indicate that the interfacial charge transfer capabilities of the GT-12 electrode are the most promising among the investigated samples characterized by the lowest R_{ct} and greatest CPE-n value.

4. Conclusion

The hydrothermal synthesis of carbon compounds obtained from green tea biomass at varied reaction periods was effectively carried out and their structural, morphological and electrochemical properties were studied. The sample

hydrothermally treated at 12 hr (GT-12) among the synthesized samples showed the best overall electrochemical performance and delivered a specific capacitance of 52 F g^{-1} . XRD examination revealed that the carbon structure was mainly disordered with some graphitic ordering and SEM confirmed the formation of a porous morphology. The FTIR analysis further identified the existence of surface functional groups that could improve the interaction with electrolyte as well as the electrochemical activity. The structural chaos, partial graphitic ordering, porous morphology and surface functions give ideal properties for electrochemical charge storage.

In general, GT-12 showed structural and morphological features that were conducive to charge storage behavior, resulting in an attractive electrical energy storage performance. The results indicate the hydrothermal green tea biomass carbon as a feasible candidate for sustainable energy storage application and further assessment can be done for anode material for sodium ion batteries in practical coin cell topologies.

REFERENCES

- Gou, G., et al., Hierarchical porous carbon electrode materials for supercapacitor developed from wheat straw cellulosic foam. *Renewable Energy*, 2020. 149: p. 208–216.
- Li, M., et al., 30 years of lithium-ion batteries. *Advanced materials*, 2018. 30(33): p. 1800561.
- Kim, H., Sodium-ion battery: can it compete with Li-ion? *ACS Materials Au*, 2023. 3(6): p. 571.
- Qiao, S., et al., Advanced anode materials for rechargeable sodium-ion batteries. *ACS nano*, 2023. 17(12): p. 11220–11252.
- Lee, S.C., et al., Mechanical activation of graphite for Na-ion battery anodes: unexpected reversible reaction on solid electrolyte interphase via x-ray analysis. *Advanced Science*, 2024. 11(28): p. 2401022.
- He, X.X., et al., Sustainable hard carbon for sodium-ion batteries: precursor design and scalable production roadmaps. *Advanced Materials*, 2025. 37(36): p. 2506066.
- Kitchamsetti, N., et al., Biomass-derived hard carbon anodes for sodium-ion batteries: recent advances in synthesis strategies. *Nanomaterials*, 2025. 15(20): p. 1554.
- Petrović, J., et al., Hydrothermal carbonization of waste biomass: a review of hydrochar preparation and environmental application. *Processes*, 2024. 12(1): p. 207.
- Liang, S., et al., Pruned tea biomass plays a significant role in functional food production: A review on characterization and comprehensive utilization of abandon-plucked fresh tea leaves. *Comprehensive Reviews in Food Science and Food Safety*, 2024. 23(4): p. e13406.
- Sekar, S., et al., Substantial LIB anode performance of graphitic carbon nanoflakes derived from biomass green-tea waste. *Nanomaterials*, 2019. 9(6): p. 871.
- Yang, G. and S.-J. Park, Conventional and microwave hydrothermal synthesis and application of functional materials: A review. *Materials*, 2019. 12(7): p. 1177.
- McGonigle, R., et al., Autoclave reactor synthesis of upconversion nanoparticles, unreported variables, and safety considerations. *Communications Chemistry*, 2025. 8(1): p. 36.
- Scherzinger, M., T. Kulbeik, and M. Kaltschmitt, Autoclave pre-treatment of green wastes—Effects of temperature, residence time and rotation speed on fuel properties. *Fuel*, 2020. 273: p. 117796.
- Schumacher, M., et al., Hydrothermal conversion of seaweeds in a batch autoclave. *The Journal of supercritical fluids*, 2011. 58(1): p. 131–135.

- Alarcón-Arroyo, M.I., et al., High-performance supercapacitor electrodes based on alpaca manure-derived porous carbons. *Electrochimica Acta*, 2025: p. 147812.
- Kang, E., et al., Highly improved rate capability for a lithium-ion battery nano-Li₄Ti₅O₁₂ negative electrode via carbon-coated mesoporous uniform pores with a simple self-assembly method. *Advanced Functional Materials*, 2011. 21(22): p. 4349–4357.
- Sa, Q. and Y. Wang, Ni foam as the current collector for high capacity C–Si composite electrode. *Journal of Power Sources*, 2012. 208: p. 46–51.
- Jiang, Y., et al., Large-surface-area activated carbon with high density by electrostatic densification for supercapacitor electrodes. *Carbon*, 2021. 175: p. 281–288.
- Zhang, M., et al., Robust graphene composite films for multifunctional electrochemical capacitors with an ultrawide range of areal mass loading toward high-rate frequency response and ultrahigh specific capacitance. *Energy & Environmental Science*, 2018. 11(3): p. 559–565.
- Cui, Z. and W. Sheng, Thoughts about choosing a proper counter electrode. *ACS Catalysis*, 2023. 13(4): p. 2534–2541.
- Fan, Z., et al., Recent developments in electrode materials for the selective upgrade of biomass-derived platform molecules into high-value-added chemicals and fuels. *Green Chemistry*, 2022. 24(20): p. 7818–7868.
- Dawkins, R.C., et al., A screen-printed Ag/AgCl reference electrode with long-term stability for electroanalytical applications. *Electrochimica Acta*, 2021. 393: p. 139043.
- Fischer, J., et al., Symmetric supercapacitors with cellulose-derived carbons and Na₂SO₄ electrolytes operating in a wide temperature range. *Journal of Energy Storage*, 2022. 55: p. 105725.
- Elkholy, A.E., F.E.-T. Heakal, and N.K. Allam, A facile electrosynthesis approach of amorphous Mn-Co-Fe ternary hydroxides as binder-free active electrode materials for high-performance supercapacitors. *Electrochimica Acta*, 2019. 296: p. 59–68.
- Thompson, M., et al., A review on biomass-derived hard carbon materials for sodium-ion batteries. *Materials Advances*, 2021. 2(18): p. 5881–5905.
- Wang, Y., et al., High capacity and high efficiency maple tree-biomass-derived hard carbon as an anode material for sodium-ion batteries. *Materials*, 2018. 11(8): p. 1294.
- Howe, J.Y., et al., Improved crystallographic data for graphite. *Powder diffraction*, 2003. 18(2): p. 150–154.
- Ramos, Y., et al. Biocarbon Synthesis Methods for Anode Electrodes: A Review. in 2024 9th International Engineering, Sciences and Technology Conference (IESTEC). 2024. IEEE.
- FARINHA, J., et al., Powering the Future.
- Titirici, M.-M., Sustainable carbon materials from hydrothermal processes. 2013: John Wiley & Sons.
- Ma, X., et al., Study of biochar properties by scanning electron microscope–energy dispersive X-ray spectroscopy (SEM-EDX). *Communications in soil science and plant analysis*, 2016. 47(5): p. 593–601.
- Amrutha, S., N. Suja, and S. Menon, Morphological analysis of Biomass, in *Handbook of Biomass*. 2023, Springer. p. 1–31.
- Freschet, G.T., E. Kichenin, and D.A. Wardle, Explaining within-community variation in plant biomass allocation: a balance between organ biomass and morphology above vs below ground? *Journal of Vegetation Science*, 2015. 26(3): p. 431–440.

- Khavryuchenko, V.D., et al., Nanostructurization in the SKS active carbon, characterized by SEM, TEM, EDX and quantum-chemical simulations. *International Journal of Modern Physics B*, 2010. 24(11): p. 1449–1462.
- Liu, F., et al., Hydrothermal carbonization of holocellulose into hydrochar: Structural, chemical characteristics, and combustion behavior. *Bioresource technology*, 2018. 263: p. 508–516.
- Yao, Y., et al., Effects of temperature and duration on the combustion characteristics of hydrochar prepared from traditional Chinese medicine residues using hydrothermal carbonization process. *International Journal of Energy Research*, 2024. 2024(1): p. 3595643.
- Dutta, S., A. Bhaumik, and K.C.-W. Wu, Hierarchically porous carbon derived from polymers and biomass: effect of interconnected pores on energy applications. *Energy & Environmental Science*, 2014. 7(11): p. 3574–3592.
- Biesheuvel, P., Y. Fu, and M.Z. Bazant, Diffuse charge and Faradaic reactions in porous electrodes. *Physical Review E—Statistical, Nonlinear, and Soft Matter Physics*, 2011. 83(6): p. 061507.
- Verma, R., et al., Comparative studies of functional groups present in invasive and economically important plant leaf methanolic extracts by using FTIR spectroscopic analysis. *GSC Biological and Pharmaceutical Sciences*, 2023. 23(3): p. 184–191.
- Pasipanodya, D., et al., Production of hydrochar from the hydrothermal carbonisation of food waste feedstock for use as an adsorbent in removal of heavy metals from water. *Biomass conversion and biorefinery*, 2025. 15(8): p. 11819–11833.
- Bedoui, A., et al., Hydrothermal carbonization of date palm pits and pine nut shells: fuel characteristics of hydrochar, and surface characteristics and adsorption application of activated hydrochar. *Comptes Rendus. Chimie*, 2024. 27(S3): p. 161–173.
- Pasieczna-Patkowska, S., M. Cichy, and J. Flieger, Application of Fourier transform infrared (FTIR) spectroscopy in characterization of green synthesized nanoparticles. *Molecules*, 2025. 30(3): p. 684.
- Daer, D., et al., Co-hydrothermal carbonization of waste biomass and phosphate rock: promoted carbon sequestration and enhanced phosphorus bioavailability. *Biochar*, 2024. 6(1): p. 70.
- Yang, L., et al., Significant roles of surface functional groups and Fe/Co redox reactions on peroxymonosulfate activation by hydrochar-supported cobalt ferrite for simultaneous degradation of monochlorobenzene and p-chloroaniline. *Journal of Hazardous Materials*, 2023. 445: p. 130588.
- Yuan, C., et al., Recent advances and challenges in biomass-derived carbon materials for supercapacitors: A review. *Fuel*, 2024. 362: p. 130795.
- Islam, M.M., A. Nafees, and V. Natarajan, Biomass-Derived Carbon Materials for Electrochemical Energy Storage: Uncertain Functionalities, Stability and Trade-offs With Heteroatom Doping. *ChemistrySelect*, 2026. 11(19): p. e73416.
- Hu, H., et al., A state-of-the-art review on biomass-derived carbon materials for supercapacitor applications: From precursor selection to design optimization. *Science of The Total Environment*, 2024. 912: p. 169141.
- Khan, A., et al., Hierarchically porous biomass carbon derived from natural withered rose flowers as high-performance material for advanced supercapacitors. *Batteries & supercaps*, 2020. 3(8): p. 731–737.

- Lu, W., et al., Biomass-derived carbon applications in the field of supercapacitors: Progress and prospects. *Chemical Engineering Journal*, 2024. 495: p. 153311.
- Xu, M., et al., Biomass-based porous carbon/graphene self-assembled composite aerogels for high-rate performance supercapacitor. *Journal of Cleaner Production*, 2021. 315: p. 128110.
- Prieto, M., et al., Hydrothermal carbonization of biomass for electrochemical energy storage: parameters, mechanisms, electrochemical performance, and the incorporation of transition metal dichalcogenide nanoparticles. *Polymers*, 2024. 16(18): p. 2633.
- Zhu, X., et al., Biomass-derived carbon and their composites for supercapacitor applications: sources, functions, and mechanisms. *EcoEnergy*, 2025. 3(3): p. e70000.
- Ngidi, N.P., A.F. Koekemoer, and S.S. Ndlela, Recent advancement in the electrochemical performance of electrochemical capacitors based on biomass-derived porous carbon: a review. *Journal of Energy Storage*, 2024. 89: p. 111638.
- Ehosioko, S., et al., Sensing the electrical properties of roots: A review. *Vadose Zone Journal*, 2020. 19(1): p. e20082.
- Magar, H.S., R.Y. Hassan, and A. Mulchandani, Electrochemical impedance spectroscopy (EIS): Principles, construction, and biosensing applications. *Sensors*, 2021. 21(19): p. 6578.
- Long, W.-J., et al., Green synthesis of biomass-derived carbon dots as an efficient corrosion inhibitor. *Journal of Molecular Liquids*, 2022. 360: p. 119522.
- Thirumal, V., et al., Characterization of activated biomass carbon from tea leaf for supercapacitor applications. *Chemosphere*, 2022. 291: p. 132931.
- Barzegar, F., et al., Cycling and floating performance of symmetric supercapacitor derived from coconut shell biomass. *AIP Advances*, 2016. 6(11).
- He, S. and W. Chen, Application of biomass-derived flexible carbon cloth coated with MnO₂ nanosheets in supercapacitors. *Journal of power sources*, 2015. 294: p. 150–158.
- Li, Y., et al., Reduced graphene oxide-TaON composite as a high-performance counter electrode for Co (bpy) 3^{3+/2+}-mediated dye-sensitized solar cells. *ACS applied materials & interfaces*, 2013. 5(16): p. 8217–8224.
- Mohamed, M.M., et al., A comprehensive evaluation of biomass-derived activated carbon materials for electrochemical applications in zinc-ion hybrid supercapacitors. *ACS Applied Energy Materials*, 2024. 7(17): p. 7517–7533.
- Acharya, T. and R. Choudhary, Structural, dielectric and impedance characteristics of CoTiO₃. *Materials Chemistry and Physics*, 2016. 177: p. 131–139.
- Cocchi, A. and A. Lampasi. Modeling Non-Ideal Behaviors of Supercapacitors' Equivalent Capacitance. in 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe). 2020. IEEE.
- Gateman, S.M., et al., On the use of a constant phase element (CPE) in electrochemistry. *Current Opinion in Electrochemistry*, 2022. 36: p. 101133.
- Malode, S.J., et al., An Electrochemical Sensing Platform Based on a Boron-Doped CaO/Zinc-Based MOF-5 Carbon Matrix for Nitroaromatic Explosive 2, 4-Dinitrotoluene in Food, Soil, and Water Samples. *ACS Applied Engineering Materials*, 2026.

- Zhang, M., et al., Eco-friendly biomass-derived porous carbon electrode for simultaneous and sensitive detection of catechol and hydroquinone. *Surfaces and Interfaces*, 2025: p. 107988.
- Huang, J.D., et al., Rapid mapping of electrochemical processes in energy-conversion devices. *Joule*, 2024. 8(7): p. 2049–2072.
- Ramesh, T., et al., Dynamic electrochemical impedance spectroscopy as a rapid screening tool for supercapacitor electrode materials. *Journal of Materials Science: Materials in Electronics*, 2020. 31(2): p. 1681–1690.
- Adam KM, Teinilä M, Mevada C, Karttaavi T, Lindsten S, Tewari A, Keskinen J, Mäntysalo M. A green approach to sustainable supercapacitors: Optimized KHCO_3 activation of carbon negative biochar. *Industrial Crops and Products*. 2026 Aug 1;250:123997.
- Fujishige M, Yoshida I, Toya Y, Banba Y, Oshida KI, Tanaka YS, Dulyaseree P, Wongwiriyan W, Takeuchi K. Preparation of activated carbon from bamboo-cellulose fiber and its use for EDLC electrode material. *Journal of Environmental Chemical Engineering*. 2017 Apr 1;5(2):1801-8.
- Yan B, Zheng J, Feng L, Du C, Jian S, Yang W, Wu YA, Jiang S, He S, Chen W. Wood-derived biochar as thick electrodes for high-rate performance supercapacitors. *Biochar*. 2022 Dec;4(1):50.
- Chalmpes N, Tantis I, Alsmail AW, Aldakkan BS, Dimitrakou A, Karakassides MA, Salmas CE, Giannelis EP. Elevating waste biomass: supercapacitor electrode materials derived from spent coffee grounds. *Energy & Fuels*. 2025 Jan 3;39(2):1305-15.
- Qu K, Wang W, Shi C, Sun Z, Qi H, Shi J, Yang S, Huang Z, Guo Z. Fungus bran-derived nanoporous carbon with layered structure and rime-like support for enhanced symmetric supercapacitors. *Journal of Nanostructure in Chemistry*. 2021 Dec;11(4):769-84.