



Exploring the effect of electrolyte on charge storage mechanisms in sustainable supercapacitor electrodes from sugarcane leaf-derived porous activated carbon

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HIGHLIGHTS

- Synthesized SLAC boosts ion flow and charge storage with its high surface area.
- Electrolyte types and concentrations impact charge storage in electrodes.
- SLAC achieved 254F/g at 0.5 A/g, driven by capacitive charge storage in a 6.00 M KOH solution.
- SLAC retained 94.48 % capacitance after 5,000 cycles, with 28 Wh kg⁻¹.

ARTICLE INFO

Keywords:

Supercapacitor
Sugarcane leaves
Porous activated carbon
Electrolyte
Electrode materials
Hydrothermal carbonization

ABSTRACT

Understanding the influence of electrolyte composition on charge storage behavior is essential for optimizing supercapacitor performance. This study explores how electrolyte type and concentration affect the electrochemical properties and storage mechanisms of porous activated carbon derived from sugarcane leaves (SLAC). With a high surface area (2006.91 m² g⁻¹) and hierarchical porosity, SLAC was evaluated in three aqueous electrolytes, H₂SO₄, Na₂SO₄, and KOH, at concentrations of 1, 3, and 6 M. Results revealed that SLAC predominantly exhibited electrical double-layer capacitance in acidic and neutral media. In contrast, under alkaline conditions, especially with 6 M KOH, a significant pseudocapacitive contribution emerged, attributed to enhanced OH⁻ ion adsorption and surface redox reactions. Notably, the 6 M KOH system achieved a maximum specific capacitance of 254 F g⁻¹ at 0.5 A g⁻¹ and excellent cycling stability with 94.48 % retention over 5,000 cycles. Kinetic analysis showed a transition from surface-controlled to diffusion-controlled charge storage with increasing KOH concentration. This work addresses a key knowledge gap by systematically correlating electrolyte characteristics with charge storage mechanisms in biomass-derived carbons. The study demonstrates that optimizing electrolyte identity and concentration, in conjunction with a well-designed hierarchical pore structure, can significantly enhance ion transport and capacitance. The findings provide a novel strategy for tuning electrochemical behavior in sustainable carbon-based supercapacitors, offering valuable insights for the development of high-performance energy storage devices.

1. Introduction

Electrolyte systems are pivotal in determining the electrochemical performance of supercapacitors, especially electric double-layer capacitors (EDLCs) (Lu et al., 2024; Brintakis et al., 2019). Unlike batteries, which store charge via redox reactions, EDLCs operate through

electrostatic interactions between electrolyte ions and electrode surfaces, entirely avoiding chemical transformations (Rajasekaran et al., 2023; Patel et al., 2024). This purely physical charge storage mechanism facilitates rapid charge/discharge kinetics, high power density, and exceptional cycling stability (Wanchan et al., 2025). Consequently, EDLCs have become highly attractive for applications demanding these

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<https://doi.org/10.1016/j.biortech.2025.133303>

Received 22 July 2025; Received in revised form 8 September 2025; Accepted 8 September 2025

Available online 9 September 2025

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properties, such as electric vehicles, backup power systems, and portable electronics (Yeetsorn et al., 2020). Although significant progress has been made in developing advanced porous carbon electrode materials, optimizing electrolyte systems remains a critical factor for maximizing overall device performance (Lu et al., 2024; Mendhe and Panda, 2023). Key electrolyte parameters, including its type, concentration, and ionic characteristics, directly govern ion transport, the formation and structure of the electric double layer, and ultimately, the energy storage capability of the device (Rawal et al., 2018; Sharma and Chand, 2023; Hur et al., 2023). Aqueous electrolytes such as sulfuric acid (H_2SO_4), potassium hydroxide (KOH), and sodium sulfate (Na_2SO_4) are widely used in supercapacitor systems due to their high ionic conductivity, low cost, and environmental friendliness (Rajasekaran et al., 2023; Wu et al., 2013; Karakehya, 2023; Wu et al., 2006). Despite these advantages, each electrolyte exhibits distinct physicochemical properties that influence charge storage mechanisms and overall device performance (Olabi et al., 2023; Liu et al., 2020). H_2SO_4 offers high proton (H^+) mobility and extremely small ionic size, enabling rapid ion transport and efficient electrical double-layer formation at the electrode-electrolyte interface (Wu et al., 2013; Karakehya, 2023; Jayachandran and Kishore babu S, Maiyalagan T, Kannan MR, Goutham kumar R, Sheeba Sherlin Y, , 2021). KOH, as a strong alkaline electrolyte, provides hydroxide ions (OH^-) with relatively small, hydrated radii, promoting deeper penetration into porous carbon networks (Rajasekaran et al., 2023). Additionally, the alkaline environment facilitates deprotonation of surface functional groups, improving electrode wettability and enhancing ion accessibility, particularly beneficial in carbons with hierarchical porosity (Qiu et al., 2023; Gao et al., 2015; Kerisit et al., 2014). In contrast, Na_2SO_4 is chemically stable and non-corrosive, making it a safe and durable choice. However, the relatively large size and high hydration energy of Na^+ ions limit their diffusion through micropores, often resulting in lower specific capacitance compared to acidic or alkaline counterparts (Rajasekaran et al., 2023; Gajewska et al., 2023). These variations in ion size, hydration characteristics, and interfacial interactions underscore the critical importance of electrolyte selection in tuning electrochemical behavior (Kerisit et al., 2014). A deeper understanding of these electrolyte-dependent mechanisms is essential for the rational design of biomass-derived carbon electrodes aimed at achieving high-performance, sustainable energy storage solutions.

Among aqueous electrolytes, KOH has garnered significant attention due to its favorable electrochemical properties and its capacity to modify electrode surface chemistry (Zhang et al., 2012). Specifically, the interaction of OH^- ions with functional groups on carbon surfaces promotes deprotonation, thereby enhancing ion accessibility and facilitating electric double-layer formation (Wei et al., 2021). Notably, while KOH is extensively utilized in supercapacitor research, comprehensive investigations into its concentration-dependent effects, principally when paired with biomass-derived porous carbons, remain scarce (Lu et al., 2024; Wu et al., 2006; Zhang et al., 2012; Sylla et al., 2019). Although higher KOH concentrations can improve ion availability and ionic conductivity, excessively concentrated solutions may induce detrimental increases in viscosity and internal resistance (Lim et al., 2022). Consequently, elucidating this trade-off is critical for optimizing electrolyte concentration to achieve high-performance supercapacitors (Yogesh et al., 2024). Furthermore, principles of chemical kinetics govern electrolyte temperature effects and ion mobility (Sharma and Chand, 2023). Elevated temperatures typically enhance ion diffusion and conductivity by lowering the energy barriers for ion transport (Zheng et al., 2015). This relationship often exhibits Arrhenius-type behavior, wherein electrolytes with lower activation energies enable faster ion movement at a specific temperature (Shi et al., 2025; Zhao et al., 2025). While temperature-dependent phenomena are not the primary focus of this work, understanding these kinetic principles provides a valuable framework for interpreting ion transport dynamics under varying operational conditions (Sylla et al., 2019). Another crucial consideration is the acid-based nature of electrolyte and its profound influence on

electrode surface chemistry. Functional groups prevalent on activated carbon surfaces (e.g., hydroxyl, carboxyl, carbonyl) undergo protonation or deprotonation depending on pH, significantly altering surface charge and wettability (Li et al., 2020; Phakkhawan et al., 2022). In alkaline media such as KOH, deprotonation enhances surface hydrophilicity and promotes electrolyte penetration into pores, thereby improving double-layer formation and capacitance (Wu et al., 2013; Zhang et al., 2012). Conversely, in acidic electrolytes like H_2SO_4 , protonation of these functional groups can restrict electrochemical accessibility and diminish capacitance (Rajasekaran et al., 2023; Taer et al., 2023). These pronounced surface interactions underscore the fundamental importance of tailored electrolyte chemistry in designing advanced supercapacitor systems. Although the properties of electrolytes play a crucial role in supercapacitor performance, most existing research has predominantly focused on the development of electrode materials, with limited systematic investigation into the influence of electrolyte type and concentration on charge storage behavior (Lakshmi and Vedhanarayanan, 2023; Unknown et al., 2021; Okonkwo et al., 2021). This gap is particularly pronounced in studies involving carbon electrodes derived from underutilized biomass sources. To address this shortcoming, the present study examines the role of electrolyte identity and concentration in modulating the electrochemical performance of porous activated carbon synthesized from sugarcane leaves, an abundant and largely neglected agricultural residue. Annually, over 18 million tons of sugarcane leaves are generated in countries like Thailand, a leading sugar producer. These leaves are often discarded or incinerated post-harvest, contributing significantly to PM_{2.5} emissions and exacerbating regional air pollution (Jarumaneeroj et al., 2021; Kumar et al., 2020). While sugarcane bagasse, the fibrous byproduct of juice extraction, has been extensively investigated for bioenergy and carbon-based applications, sugarcane leaves remain largely underexploited despite their comparable lignocellulosic composition (Jarumaneeroj et al., 2021; Ratanamane et al., 2022). Utilizing sugarcane leaves as a precursor for high-performance carbon electrode materials not only promotes waste valorization but also aligns with sustainable energy and environmental management goals. Recent studies highlight the synergy between carbon structure design and electrolyte engineering for advanced energy storage. Functionalized graphene microspheres (Shi et al., 2025), wood-derived BCN-doped carbons (Zhao et al., 2025), and functionalized graphene ribbons (Miao et al., 2024) have demonstrated high volumetric or areal capacitance, while electrolyte innovations such as dipole-dipole interaction-driven ion desolvation further emphasize the critical role of electrolyte chemistry (Liu et al., 2025). These advances underscore the importance of integrating electrode architecture with electrolyte optimization, directly motivating the present work. This work aims to bridge the existing research gap by providing new insights into how electrolyte selection interacts with biomass-derived porous carbon structures to optimize supercapacitor performance.

This work introduces a sustainable strategy for fabricating carbon electrodes by employing sugarcane leaves, an abundant yet underutilized agricultural residue, as a precursor for activated carbon (SLAC) (Wanchan et al., 2025). The synthesis was carried out through a two-step process: hydrothermal carbonization (HTC) to generate biochar, followed by chemical activation with potassium carbonate (K_2CO_3) to develop hierarchical porosity and increase the specific surface area. The use of HTC is particularly advantageous, as its relatively mild conditions retain oxygen-containing functional groups and yield a reactive hydrochar framework. This structural advantage enables more efficient and controllable pore formation during the subsequent activation step, outperforming conventional high-temperature or single-step approaches (Hur et al., 2023; Ojewumi and Chen, 2024). The structural and textural properties of the resulting SLAC were comprehensively characterized using X-ray diffraction (XRD), Nitrogen adsorption-desorption (BET analysis), Raman spectroscopy, and scanning electron microscopy (SEM). To fill the research gap concerning the limited understanding of

electrolyte effects on biomass-derived carbons, the electrochemical behavior of SLAC was systematically evaluated in three aqueous electrolytes, H_2SO_4 , Na_2SO_4 , and KOH , at varying concentrations (1, 3, and 6 M). Electrochemical measurements, including cyclic voltammetry (CV), galvanostatic charge–discharge (GCD), and electrochemical impedance spectroscopy (EIS), were used to assess specific capacitance, charge retention, and ion diffusion kinetics. This work distinguishes itself by establishing clear structure–property–performance relationships, linking electrolyte characteristics, such as ion size, hydration radius, and mobility, to the electrochemical responses of the SLAC electrodes. By adopting an electrolyte-focused design strategy, the study provides new insights into electrode–electrolyte interactions that govern charge storage behavior. Moreover, through targeted analysis of KOH concentration effects, this research offers practical guidance for optimizing performance while promoting environmentally and economically sustainable energy storage technologies. In essence, this research demonstrates that electrolytes transcend their auxiliary role to become key design parameters in developing high-performance supercapacitors. Our in-depth investigation of ion transport dynamics, electric double-layer formation, and surface chemistry interactions contributes significantly to advancing green and scalable energy storage technologies utilizing biomass-derived carbon materials.

2. Experimental section

2.1. Synthesis of sugarcane leaf-derived porous activated carbon

Sugarcane leaves (SL), sourced from Mitrphol Sugar Corp. Ltd. (Thailand), were crushed and ball-milled into a fine powder. The powder was sieved through a 250 μm mesh, washed three times with deionized water to remove soil impurities, and dried overnight at 105 $^{\circ}\text{C}$ to eliminate moisture. Subsequently, the dried SL powder underwent HTC in Parr reactors at 240 $^{\circ}\text{C}$ for 90 min after mixing with deionized water. The resulting slurry was washed with deionized water and dried overnight at 105 $^{\circ}\text{C}$ to yield SL-biochar. For chemical activation, SL-biochar was thoroughly mixed with a K_2CO_3 solution at a 1:1 mass ratio, dried at 110 $^{\circ}\text{C}$ to evaporate the solvent, and then transferred to a crucible. The sample was activated in a horizontal tube furnace at 800 $^{\circ}\text{C}$ for 2 h under a nitrogen atmosphere (99.999 % purity, 200 mL/min flow rate). Following activation, the product was washed with 1.0 M HCl to

remove residual organics, rinsed with deionized water until neutral pH ($\text{pH} \approx 7$), and dried overnight at 105 $^{\circ}\text{C}$. The final material was designated as sugarcane leaf-derived activated carbon (SLAC). The overall preparation process is illustrated in Fig. 1.

2.2. Characterizations of sugarcane leaf-derived activated carbon

Morphology, microstructure, and elemental composition were examined using field emission scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy (FE-SEM/EDS; Hitachi SU8030) and transmission electron microscopy coupled with EDS (TEM/EDS; JEOL TEM-2100). Nitrogen adsorption–desorption isotherms were collected at -196 $^{\circ}\text{C}$ using an Autosorb IQ analyzer following sample degassing at 300 $^{\circ}\text{C}$ under vacuum for 3 h. Specific surface area was calculated using the Brunauer–Emmett–Teller (BET) method, while pore size distribution was evaluated via the density functional theory (DFT) model. Crystalline phases were identified by X-ray diffraction (XRD; Bruker D8 Advance) using $\text{Cu K}\alpha$ radiation ($\lambda = 1.54$ $\text{\AA}$, 40 kV, 40 mA), with scans performed over a 2θ range of 10° – 80° at a step size of 0.02° and a step time of 0.5 s/degree. The degree of graphitization was assessed through Raman spectroscopy (NT-MDT NTEGRA) with 532 nm laser excitation. Surface elemental composition was further analyzed by X-ray photoelectron spectroscopy (XPS) with an $\text{Al K}\alpha$ X-ray source (1487 eV) on a ULVAC-PHI, Inc. instrument. Spectral deconvolution and peak fitting were performed with a Shirley background and Gaussian–Lorentzian peak shapes to determine the chemical states of surface elements.

2.3. Electrode fabrication and supercapacitor performance tests

Working electrodes were fabricated by thoroughly mixing the active material (80 wt%), carbon black (10 wt%), and polyvinylidene fluoride (PVDF, 10 wt%). *N*-methyl-2-pyrrolidone (NMP, 1.00 mL) was added to the mixture, followed by 1 h of sonication to form a homogeneous slurry. This slurry was cast onto a nickel foam substrate (2.0×1.0 cm^2), confining the active material to a 1.0×1.0 cm^2 area. The coated substrate was then dried at 80 $^{\circ}\text{C}$ for 24 h to evaporate the solvent, yielding electrodes with an average active mass loading of ~ 5.00 mg cm^{-2} . Electrochemical measurements employed a two-electrode symmetric cell configuration using 6.0 M KOH as the electrolyte. An electrolyte-

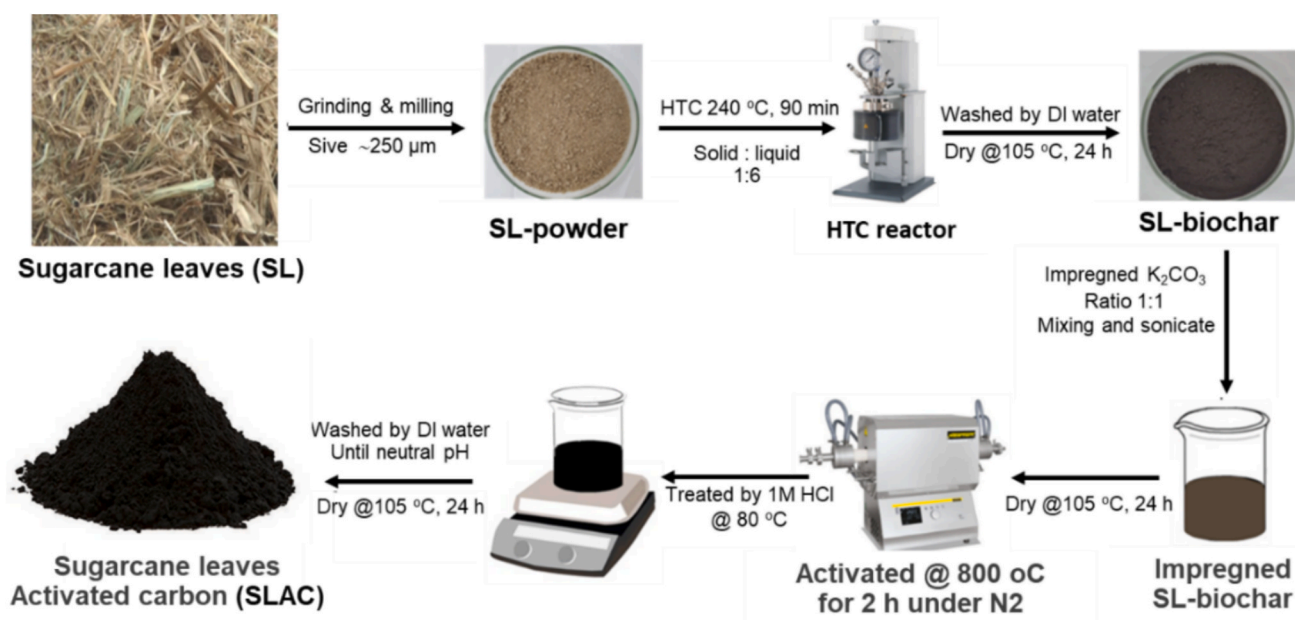


Fig. 1. Schematic of the preparation process for sugarcane leaf-derived activated carbon.

soaked porous paper separator was placed between the electrodes to prevent electrical contact.

Supercapacitor performance was evaluated through CV, GCD, and EIS. Cyclic voltammetry was carried out in the potential range of 0.0–1.0 V with scan rates of 1–100 mVs⁻¹ to explain the redox behavior and capacitance of supercapacitor electrodes. The specific capacitance (C_{sp}) was calculated from CV results using well-defined relations (Helseth, 2021);

$$C_{sp}(F/g) = \frac{\int i dv}{m S \Delta V} \quad (1)$$

Where i stands for the integrated area of the CV curve (V), m is the mass loading of active material in g, S denotes the scan rate (Vs⁻¹), and ΔV represents the potential range (V). The galvanostatic charge/discharge (GCD) test was used to evaluate the energy storage and charge/discharge of the supercapacitor. The data from the GCD curve was used to calculate the specific capacitance, following the equations (Sharma and Chand, 2023);

$$\text{Specific capacitance (CSC)} = \frac{ix\Delta t}{m \Delta V} \quad (2)$$

where i is for the applied current (A), Δt represents the discharge time, m is the mass loading of active material in g, and ΔV denotes the potential range (V).

The energy density and power density were calculated based on the following equations (Sharma and Chand, 2023):

$$\text{Energy density (E)} = \frac{C_s \Delta V^2 \times 1000}{2 \times 3600} \quad (3)$$

$$\text{Power density (P)} = \frac{3600E}{\Delta t} \quad (4)$$

3. Results and discussion

3.1. Physicochemical characteristics of SLAC-supercapacitor electrode

The crystallographic structure of the synthesized SLAC material was examined via X-ray diffraction (XRD), as shown in Fig. 2(a). The XRD profile reveals two characteristic diffraction peaks at $2\theta = 26.14^\circ$ and 42.55° , corresponding to the (002) and (101) planes of graphitic and amorphous carbon, respectively. The sharp (002) reflection suggests a relatively high degree of graphitization compared to conventional activated carbons in prior studies (Phakkhawan et al., 2022; Mohit and Hashmi, 2022; Sarkar et al., 2020; Jain and Tripathi, 2015; Lobato-Peralta et al., 2023; Dhelipan et al., 2017). This structural improvement is attributed to the combined effects of HTC and chemical activation. HTC promotes the initial formation of an ordered carbon matrix through biomass dehydration, decarboxylation, and polymerization (Nicolae et al., 2020; Wang et al., 2018). Subsequent activation with K_2CO_3 at elevated temperatures further modifies the structure. During thermal decomposition, K_2CO_3 generates K_2O , CO_2 , and CO , which promote the reorganization of carbon atoms into graphitic domains

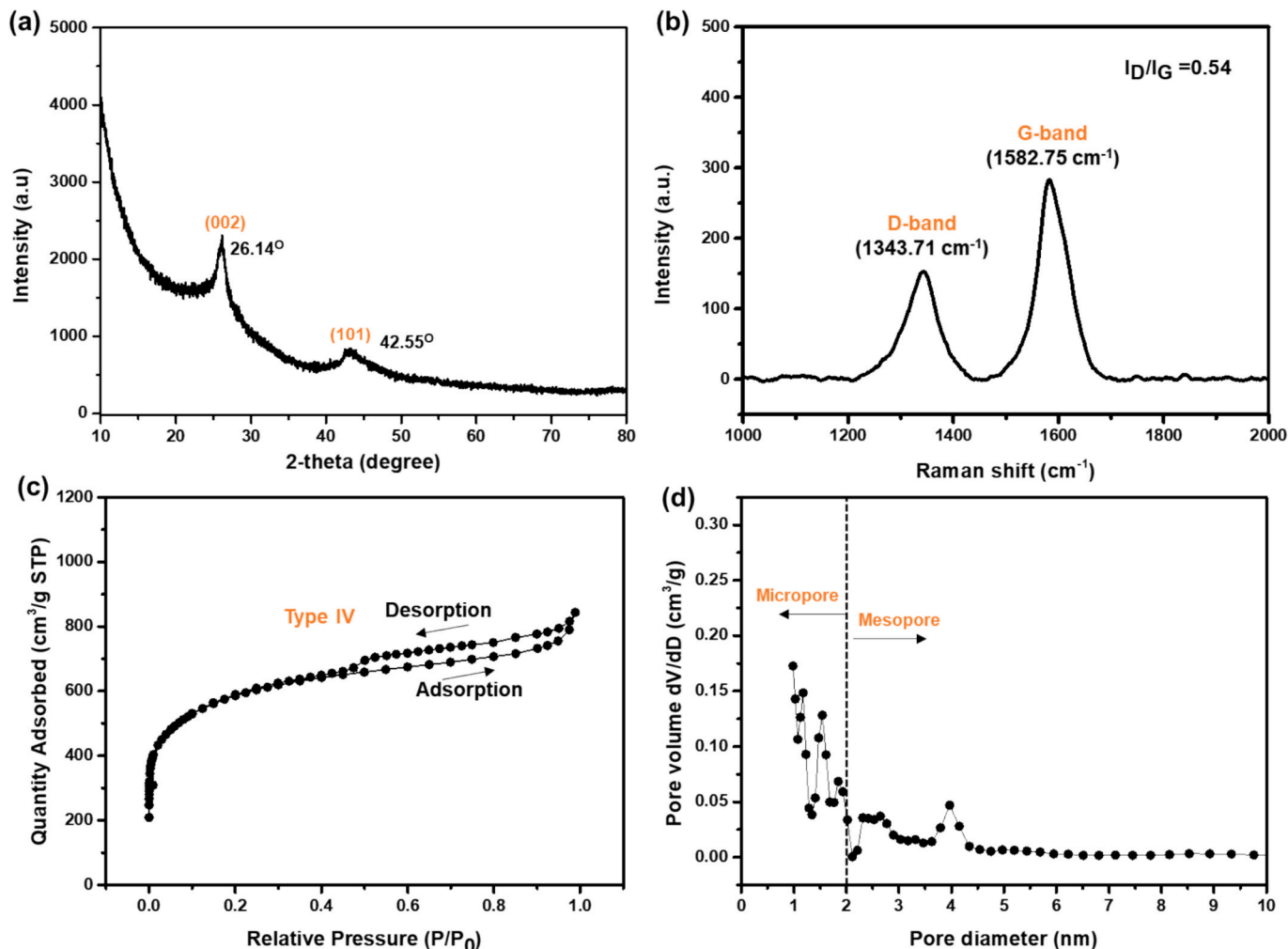


Fig. 2. (a) XRD pattern, (b) Raman spectra, (c) N₂ adsorption-desorption isotherms, and (d) pore size distribution plot of SLAC sample.

(Wang et al., 2020; Kopyscinski et al., 2014). Concurrently, potassium species (K and K₂O) intercalate between carbon layers, inducing lattice expansion. Upon potassium evaporation at high temperatures, the residual carbon framework adopts a more ordered configuration, enhancing graphitic ordering and electrical conductivity (Li et al., 2024). The presence of an amorphous phase suggests the retention of oxygen-containing functional groups (e.g., -OH, -COOH), which influence electrolyte interaction and ion intercalation behavior (Zhang et al., 2021). These interactions improve electrochemical performance by augmenting electrolyte accessibility and ion transport kinetics at the electrode–electrolyte interface (Qiu et al., 2023). This structural duality ordered graphitic domains ensuring efficient electron transport and disordered regions providing ion-accessible sites optimally balances electrical conductivity and ion diffusion, as corroborated by Raman analysis (Jia et al., 2023). The peak broadening in the XRD pattern further indicates a degree of disorder, likely due to defect sites, heteroatom doping, or residual activation byproducts, which contribute to an enhanced charge storage mechanism (Gupta, 2024; Guan et al., 2025). Overall, the combination of well-ordered graphitic structures with disordered carbon regions positions SLAC as a promising electrode material for high-performance supercapacitors.

The structural characteristics of SLAC were further examined using Raman spectroscopy, as shown in Fig. 2(b). The Raman spectrum exhibits two primary peaks: the D-band at approximately 1343.71 cm⁻¹, which is attributed to defect-induced vibrational modes in disordered carbon (sp³-hybridized carbon), and the G-band at 1582.75 cm⁻¹, associated with the E_{2g} phonon mode of sp²-hybridized carbon-carbon bonds in graphitic domains (Rawal et al., 2018; Kumar Jha et al., 2023). The intensity ratio (I_D/I_G), calculated from the maximum peak intensities, is 0.54, as listed in Table 1.

The relatively low I_D/I_G ratio indicates a high degree of graphitization, reflecting a well-organized carbon framework with fewer structural defects compared to typical activated carbons (I_D/I_G ~ 0.8–1.2) (Maslova et al., 2012). Despite the carbonization temperature (800 °C) being significantly lower than conventional graphitization temperatures (2500–3000 °C), the low I_D/I_G value suggests the formation of pseudo-graphitic domains rather than fully crystalline graphite. This partial ordering likely originates from the precursor's inherent structure and heteroatom-driven rearrangements during carbonization (Asefa and Huang, 2017). The Raman results align with XRD analysis, confirming the coexistence of both ordered graphitic and disordered carbon phases in SLAC. The reduced ID/IG ratio implies a higher degree of π - π conjugation and a lower density of lattice defects, which collectively enhance charge carrier mobility (Maslova et al., 2012; Chae et al., 2021). The dominance of sp²-hybridized carbon supports delocalized electron transport, thereby decreasing internal resistance and improving electrical conductivity. Such structural organization is particularly beneficial for electrochemical applications, as it facilitates efficient charge storage, rapid ion diffusion, and improved electrolyte accessibility at the electrode–electrolyte interface (Wang et al., 2020). Moreover, the presence of interconnected graphitic domains offers continuous pathways for ion transport while simultaneously reducing energy barriers for electrolyte penetration (Sharma and Chand, 2023). This architecture is critical for achieving high electrochemical performance, ensuring both fast charge/discharge dynamics and stable cycling behavior (Patel et al., 2024; Ngidi et al., 2024). The synergistic interplay between graphitic order and residual structural defects provides an optimal balance of electrical conductivity, ion transport, and electrochemical activity, underscoring the potential of SLAC as a high-

performance electrode material for energy storage. The pore structure characteristics and specific surface area of SLAC were analyzed using N₂ adsorption–desorption isotherms, as shown in Fig. 2(c). The isotherm exhibits a Type IV profile with an H₂-type hysteresis loop in the relative pressure (P/P₀) range of 0.4–0.9, indicating the presence of mesopores and a hierarchical porous network, by IUPAC classification (Xu et al., 2020). The initial nitrogen uptake at low relative pressures (P/P₀ < 0.1) further confirms the presence of micropores. The H₂-type hysteresis loop suggests ink-bottle-shaped mesopores, characterized by narrow pore entrances and wider internal cavities, which can enhance ion confinement but may also impede ion transport if excessive structural complexity is present. The textural properties of the SLAC electrodes are summarized in Table 2. The SLAC electrode exhibits a high specific surface area of 2,006.91 m² g⁻¹, primarily due to the activation effect of K₂CO₃, which facilitates the formation of a hierarchical pore structure (Wang et al., 2020). The micropore and mesopore surface areas are 782.3 and 1,224.59 m² g⁻¹, respectively, corresponding to a micropore-to-mesopore ratio of 0.39:0.61. This well-balanced ratio favors supercapacitor performance by simultaneously supporting high energy and power densities. Micropores (<2 nm) serve as active sites for ion adsorption and electric double-layer formation, directly contributing to high specific capacitance. Meanwhile, mesopores (2–50 nm) facilitate rapid ion transport by reducing diffusion resistance and enhancing electrolyte penetration (Zhu et al., 2025). The pore size distribution (Fig. 2(d)) confirms the dominance of micropores, while the interconnected mesopores act as transport highways that mitigate ion confinement and internal resistance. Although micropores provide a large electrochemically accessible surface area, excessive microporosity can hinder electrolyte infiltration and slow charge–discharge rates. Conversely, high mesoporosity enhances ion mobility but may reduce the overall surface area, lowering charge storage capacity. Therefore, an optimal micropore-to-mesopore ratio is essential to balance charge storage and ion kinetics. In SLAC, the tailored hierarchical porosity achieved via K₂CO₃ activation enables effective ion diffusion and high capacitance (Kopyscinski et al., 2014). The interconnected network minimizes tortuosity and ensures continuous pathways for ion transport (Ngidi et al., 2024; Zhu et al., 2025). Overall, the synergy between micropores and mesopores underpins the excellent electrochemical performance of SLAC, making it a promising electrode material for next-generation energy storage applications. The outstanding electrochemical performance of SLAC can be attributed to the synergistic interplay between its micropores and mesopores, which together establish a hierarchical pore network well-suited for next-generation energy storage devices. This architecture, characterized by interconnected micro- and mesoporous domains, simultaneously supports high capacitance and excellent rate capability. Although heteroatom-doped carbons often rely on deliberately engineered pore size distributions to optimize the mesopore-to-micropore ratio for efficient ion transport (Xia et al., 2008; Tang et al., 2022), SLAC attains a comparable balance inherently through its activation process. Specifically, the micropores provide extensive surface area for charge storage, while the mesopores function as ion transport channels, enabling rapid electrolyte penetration even at elevated current densities. This natural integration of micro- and mesopores highlights the critical role of hierarchical porosity in boosting electrochemical performance, eliminating the need for additional doping or templating strategies. (Yang et al., 2017).

The surface chemistry of carbon electrodes plays a pivotal role in governing the electrochemical behavior of supercapacitors, particularly in terms of ion diffusion, charge transport, and electrical conductivity. XPS was employed to analyze the surface elemental composition and chemical bonding characteristics of SLAC, providing insights into its functional groups that directly impact these key properties. Fig. 3(a) shows the wide-scan XPS spectrum of the SLAC electrode, revealing characteristic peaks of C 1 s and O 1 s at 284.8 eV and 532.7 eV, respectively (Li et al., 2020; Kumar Jha et al., 2023). The C 1 s spectrum, shown in Fig. 3(b), is deconvoluted into four Gaussian peaks at binding

Table 1

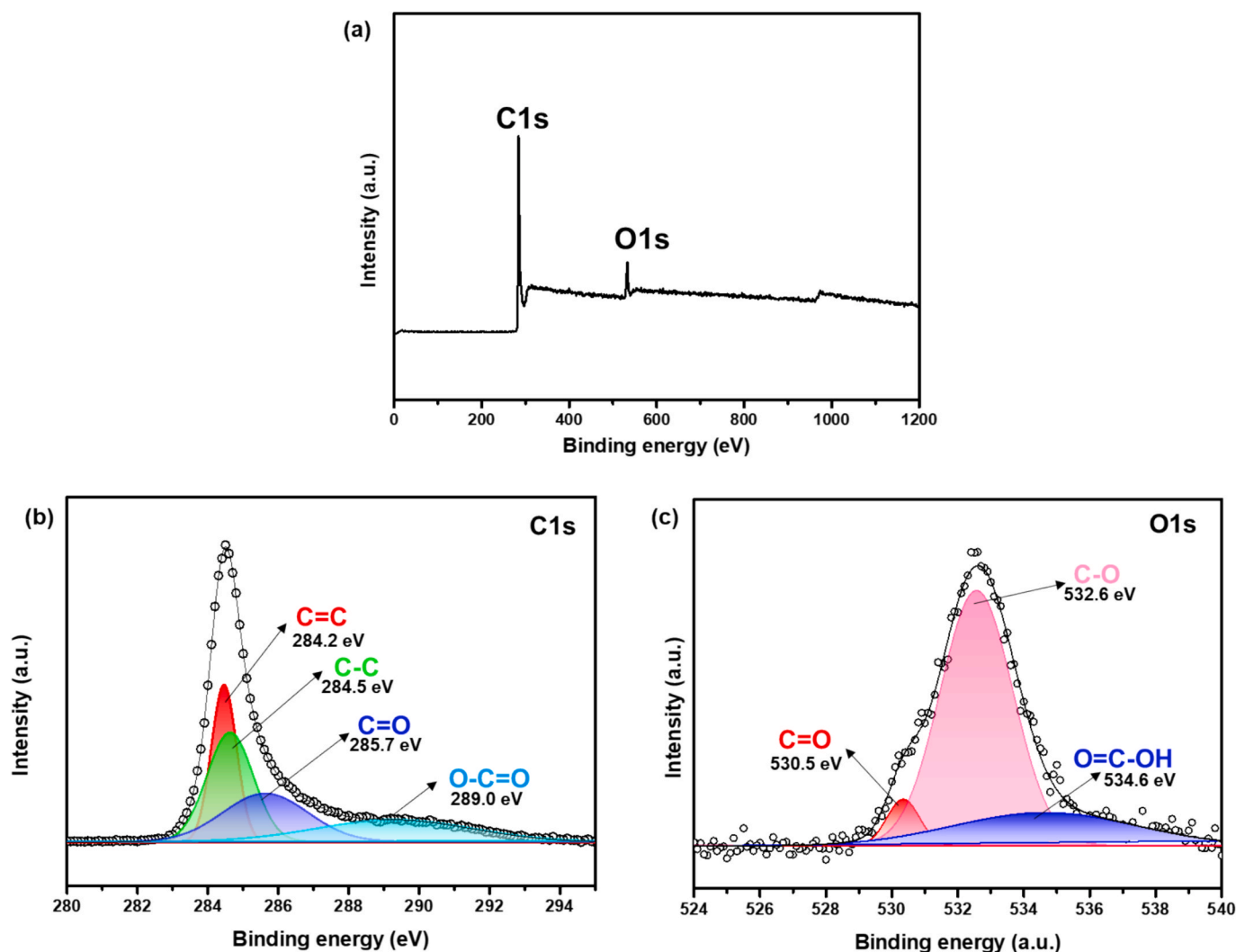
The peak position and peak intensity ratio of D-band and G-band.

Samples	Peak position		Peak intensity		I _D /I _G
	D-band	G-band	I _D	I _G	
SLAC	1343.71	1582.75	150.57	278.96	0.54

Table 2

Textural properties of SLAC electrode.

Sample	$S_{\text{BET}}^{\text{a}}$ (m^2/g)	$S_{\text{micro}}^{\text{b}}$ (m^2/g)	$S_{\text{meso}}^{\text{b}}$ (m^2/g)	$S_{\text{micro}}/S_{\text{BET}}$	$S_{\text{meso}}/S_{\text{BET}}$	$S_{\text{meso}}/S_{\text{micro}}$	Pore diameter
SLAC	2006.91	782.32	1224.59	0.39	0.61	1.56	1.70

^a BET specific surface area.^b Micropore surface area from *t*-plot method.^c Pore diameter from DA method.^d Micropore–mesopore volume from DFT method.**Fig. 3.** XPS spectra of survey scan B) C1s, and (C) O1s XPS spectra of the SLAC sample.

energies of 284.2, 284.5, 285.7, and 289.0 eV, corresponding to C=C, C—C, C=O, and O—C=O bonds, respectively. The C 1 s spectrum indicates a well-ordered carbon framework with functionalized surface chemistry that directly impacts the supercapacitor's performance by influencing electrical conductivity, ion diffusion, and EDLC behavior. The presence of C=C bonds suggest a high content of sp²-hybridized carbon, which is critical for maintaining low internal resistance and facilitating rapid charge transport, thereby enhancing power density. In contrast, C—C bonds reflect disordered or amorphous carbon structures, which, if overly abundant, could impair conductivity. In addition, functional groups such as C—O and C=O enhance wettability, facilitate electrolyte penetration, and contribute to pseudocapacitance through redox reactions, thereby increasing charge storage beyond EDLC (Kerisit et al., 2014). Excessive oxidation, however, can disrupt the carbon framework, raise charge-transfer resistance and limit rate performance.

Achieving the right balance between graphitic domains for conductivity and surface functionalities for ion transport is thus essential for high capacitance, rapid charge–discharge, and stable cycling in SLAC electrodes. Additionally, the O 1 s spectrum of the SLAC electrode, shown in Fig. 3(c), provides insight into the oxygen functional groups influencing ion transport and charge storage. The analysis identifies three primary oxygen species: C=O (530.5 eV), C—O (532.6 eV), and O—C=O (534.6 eV). C=O groups, typically associated with carbonyl structures, contribute to redox reactions that enhance charge storage capacity (Gajalakshmi et al., 2023). C—O functionalities, present in hydroxyl and ether groups, improve electrolyte interaction and facilitate ion movement across the electrode surface (Qiu et al., 2023). O—C=O species, linked to carboxyl or ester groups, assist in electrolyte accessibility but can also introduce structural defects that increase charge-transfer resistance (Gao et al., 2015). While oxygen-containing groups improve

wettability and support pseudocapacitive behavior, excessive oxidation can reduce conductivity and impair charge-transfer efficiency (Lakshmi and Vedhanarayanan, 2023; Ngidi et al., 2024). Thus, optimizing the balance of these oxygen functionalities is essential for enhancing supercapacitor performance. Properly tuned oxygen content promotes efficient ion diffusion and charge storage while ensuring long-term operational stability (Qiu et al., 2023). These findings highlight the critical role of surface chemistry in developing high-performance electrode materials.

In addition to the role of oxygen-containing functional groups in enhancing wettability and contributing to surface redox reactions, intentional heteroatom doping has been widely reported to further improve the capacitive performance of biomass-derived carbons. For instance, N/O co-doping can significantly enhance surface wettability and introduce additional redox-active sites, thereby improving ion accessibility and pseudocapacitive contribution. Similarly, B/N co-doping has been shown to promote charge transfer efficiency through synergistic electronic effects between heteroatoms, facilitating faster electron transport across the carbon framework. While the present study did not incorporate heteroatom doping strategies, these findings suggest that the pseudocapacitive behavior of SLAC could be further optimized in future work by employing N- or B-doping, particularly under alkaline electrolytes where surface redox reactions are more pronounced. This highlights a potential direction for extending the performance of sustainable sugarcane leaf-derived carbons. (Yang et al., 2025).

To study the pore morphology and surface characteristics of the activated carbon, transmission electron microscopy (TEM) and scanning electron microscopy (SEM) were utilized. As illustrated in Fig. 4(a–b), the SEM images reveal a hierarchically porous structure with rough and irregular surfaces. The material comprises fragmented carbon particles exhibiting interconnected mesopores (2–50 nm) and micropores (<2 nm), as marked in Fig. 4(a). The presence of enlarged channels and cracks, indicated in Fig. 4(b), provides effective ion diffusion pathways, which are crucial for rapid charge–discharge processes in supercapacitors. (Ngidi et al., 2024). TEM analysis of the SLAC electrode (Fig. 4c) confirms the presence of well-defined micropores within the carbon matrix. These micropores, alongside coexisting mesopores, establish a hierarchical pore architecture generated during chemical activation and carbonization. This hierarchical structure significantly enhances the specific surface area, facilitating efficient electrolyte ion adsorption and thereby contributing to high double-layer capacitance. Furthermore, the multimodal pore network promotes rapid ion accessibility and transport kinetics, ultimately enhancing the overall electrochemical performance (Zheng et al., 2015).

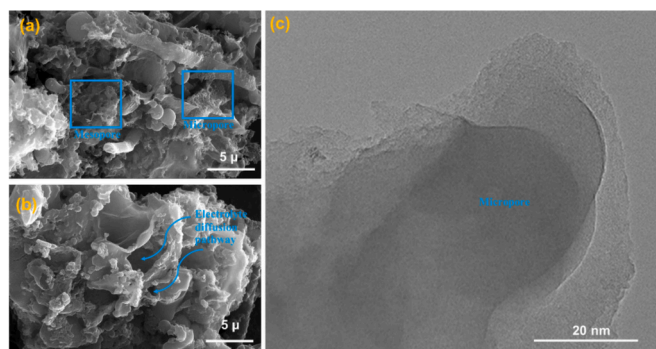


Fig. 4. (a),(b) FE-SEM images and (c) HRTEM of the synthesized SLAC electrode.

4. Electrochemical performance of SLAC as a supercapacitor electrode

4.1. Impact of electrolyte selection on the porous structure of the SLAC electrode

Electrolyte selection plays a pivotal role in determining supercapacitor performance, as ionic species in aqueous media directly influence pore accessibility and, consequently, capacitance, rate capability, energy and power densities, and cycling stability (Patel et al., 2024; Mendhe and Panda, 2023). In this study, three electrolytes, 1.0 M H_2SO_4 , Na_2SO_4 , and KOH , were employed to represent acidic, neutral, and alkaline conditions, respectively. The primary ions in each system ($\text{H}^+/\text{SO}_4^{2-}$, $\text{Na}^+/\text{SO}_4^{2-}$, and K^+/OH^-) dictate ion adsorption behavior, diffusion kinetics, and charge storage mechanisms within the porous carbon framework. Variations in ionic radius, mobility, and hydration characteristics significantly affect interfacial interactions and electrochemical responses, ultimately influencing both energy storage efficiency and long-term cycling stability. Fig. 5(a) displays cyclic voltammetry (CV) profiles of the SLAC electrode in three distinct electrolytes at a scan rate of 10 mV s^{-1} over a 0.0 to 1.0 V potential window. The CV curve in 1.0 M KOH demonstrates a near-rectangular shape, characteristic of EDLC behavior, reflecting efficient charge storage with minimal pseudocapacitive contributions (Mondal et al., 2021). In contrast, the CV profile in 1.0 M H_2SO_4 exhibits a semi-rectangular morphology with slight distortion, indicative of mixed EDLC and pseudocapacitive mechanisms. The smaller enclosed area of this curve signifies reduced capacitance relative to KOH . Similarly, the CV curve in 1.0 M Na_2SO_4 shows significant distortion between 0.4 to 1.0 V, pointing to diminished specific capacitance and charge storage efficiency. These disparities arise from differences in ionic properties (e.g., size, mobility) across electrolytes, which govern ion accessibility within the carbon pores (Wu et al., 2013; Jayachandran and Kishore babu S, Maiyalagan T, Kannan MR, Goutham kumar R, Sheeba Sherlin Y, , 2021). Fig. 5(c) depicts the scan-rate-dependent specific capacitance (5 to 100 mV s^{-1}). All electrolytes exhibit capacitance decay with increasing scan rates, a phenomenon driven by diffusion constraints and limited utilization of the porous electrode structure. At low scan rates (e.g., 5 mV s^{-1}), ions fully penetrate the electrode pores, maximizing charge storage. At higher rates, restricted ion diffusion confines charge accumulation to the electrode surface, lowering capacitance. Specific capacitance values at 5 mV s^{-1} are 99.7 F g^{-1} (H_2SO_4), 109.7 F g^{-1} (Na_2SO_4), and 145.0 F g^{-1} (KOH), highlighting KOH 's superior performance.

To achieve more precise capacitance measurements, galvanostatic charge–discharge (GCD) tests were performed. Fig. 5(b) presents the GCD curves of the SLAC electrode at 0.5 A g^{-1} , which are essential for calculating specific capacitance based on the discharge slopes in different electrolytes (Rajasekaran et al., 2023). The results show that the charge–discharge profiles follow a nearly linear pattern, indicative of ideal capacitive behavior. The symmetric triangular shape of the curves reflects good capacitive performance with minimal resistive losses. Notably, the GCD curves in KOH electrolyte exhibit longer charge and discharge times compared to those in Na_2SO_4 and H_2SO_4 , suggesting a higher energy density due to greater charge storage capacity. Moreover, the slope of the discharge curve is directly linked to power density, with a steeper slope (faster voltage drop) indicating higher power delivery but reduced energy retention (Sylla et al., 2019). The capacitive performance of the SLAC electrode across different electrolytes is strongly influenced by ionic size and diffusion behavior, both of which critically impact charge storage efficiency. Among the tested systems, 1.0 M KOH exhibited the highest specific capacitance (150 F g^{-1}), outperforming 1.0 M Na_2SO_4 (107.5 F g^{-1}) and 1.0 M H_2SO_4 (89.0 F g^{-1}). This enhancement is primarily attributed to the smaller ionic radius and higher mobility of K^+ (0.133 nm) and OH^- ions, which facilitate faster ion transport and efficient charge accumulation within the porous carbon matrix. Beyond ion size and diffusivity, electrolyte dissociation

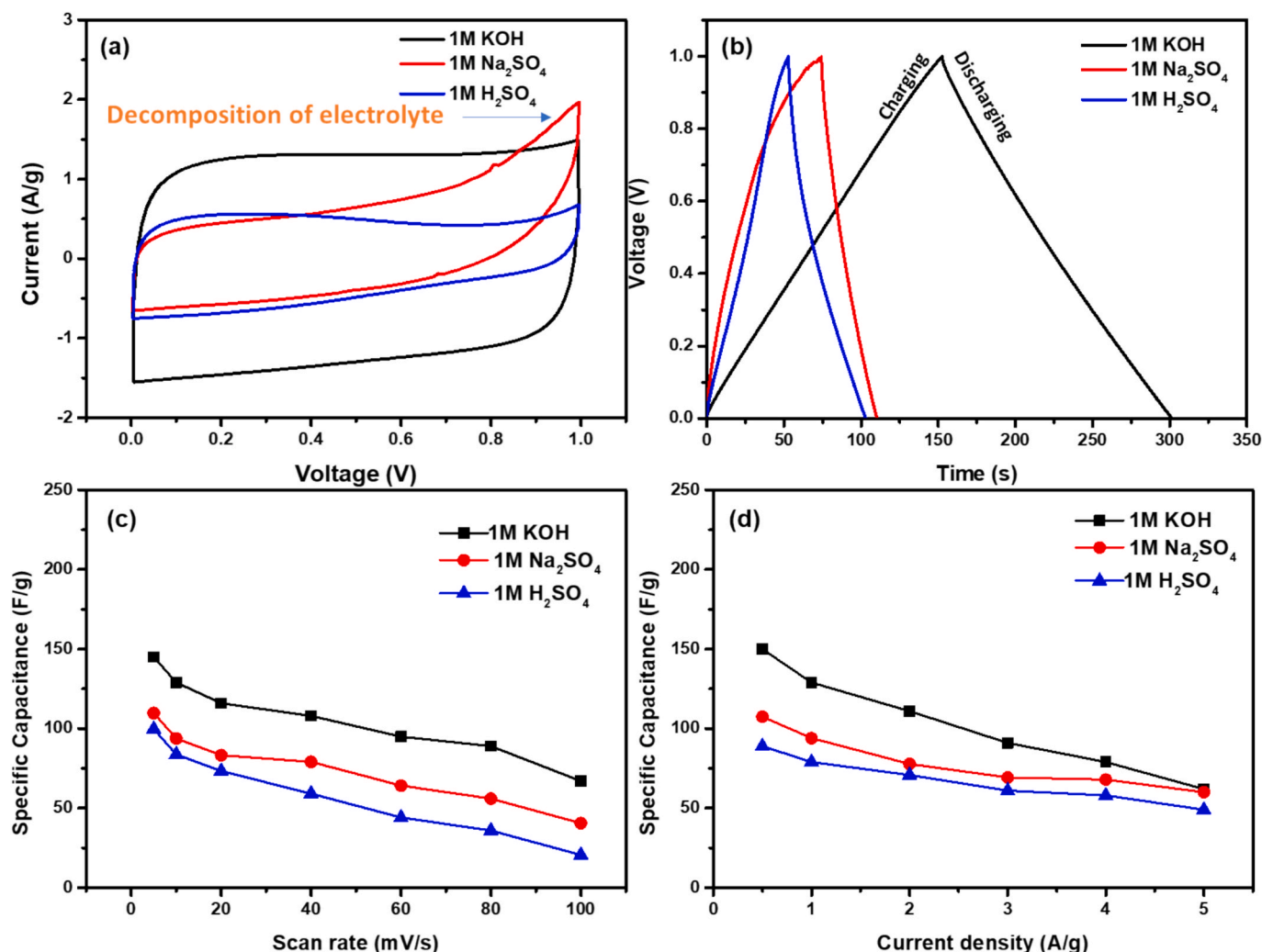


Fig. 5. CV curves (a) and GCD curve at 0.5 A g⁻¹ (b) specific capacitance (c) and (d) of the SLAC electrode with different electrolytes 1 M KOH, 1 M Na₂SO₄, and 1 M H₂SO₄.

behavior significantly affects charge storage mechanisms. H₂SO₄, a diprotic acid with two dissociation steps ($K_{a1} \approx 10^3$; $K_{a2} \approx 1.2 \times 10^{-2}$), generates a high proton concentration, inducing a highly acidic environment. While this can contribute to pseudocapacitive effects, the large hydrated ions such as H₃O⁺ and SO₄²⁻ hinder micropore accessibility and increase charge transfer resistance. In contrast, KOH, a fully dissociating strong base, provides a high concentration of OH⁻ ions that facilitate the deprotonation of oxygen-containing surface groups, enhancing surface ionization, lowering charge transfer resistance, and improving ion transport kinetics. Na₂SO₄, as a neutral salt, lacks significant acid-base reactivity, leading to pure EDLC behavior with negligible faradaic contributions. Moreover, the relatively larger ionic radii and lower mobility of Na⁺ (0.181 nm) and SO₄²⁻ (0.230 nm) result in slower diffusion and reduced accessibility to micropores. Similarly, the inferior performance of H₂SO₄ can be ascribed to the large hydrated H₃O⁺ and SO₄²⁻ species, which limit ion penetration and elevate resistance to charge transfer (Rajasekaran et al., 2023; Mendhe and Panda, 2023; Jayachandran and Kishore babu S, Maiyalagan T, Kannan MR, Goutham kumar R, Sheeba Sherlin Y, 2021; Gajewska et al., 2023). These findings highlight the critical role of electrolyte composition in tuning the balance between energy density, power density, and ion transport dynamics, thereby guiding the rational design of high-performance supercapacitor systems.

4.2. Influence of electrolyte concentration on charge storage and ion diffusion in SLAC electrode

Based on the test results presented in the previous section, it was observed that 1.0 M KOH electrolytes exhibited the highest charge density, which is appropriate for synthesized SLAC. This can be attributed to the small ionic radius of K⁺ and OH⁻ ions, which enable efficient diffusion into both micropores and mesopores, thereby enhancing the performance of the EDLC (Rajasekaran et al., 2023; Mendhe and Panda, 2023). To further investigate the observed trends, the effect of electrolyte concentration was systematically analyzed. Electrolyte concentration plays a crucial role in determining specific capacitance efficiency due to its influence on conductivity, ion mobility, ion size, and electrode-electrolyte interactions (Mendhe and Panda, 2023).

Fig. 6 (a), 6(c), and 6(e) illustrate the CV curves of SLAC samples at 1.0 M, 3.0 M, and 6.0 M KOH, which maintain a nearly rectangular shape as the scan rate increases from 5 to 100 mV s⁻¹. Fig. 7 (g) exhibits the specific capacitance decreases with increasing scan rate across all electrolyte concentrations. This phenomenon can be attributed to the limited ion diffusion within the porous electrode structure, which restricts charge storage primarily to the surface rather than allowing penetration into internal pores. At lower scan rates, ions have sufficient time to diffuse into the electrode pores, maximizing charge storage. As the scan rate increases, the response time of ions becomes insufficient to keep up with the switching of the electric field, causing charge

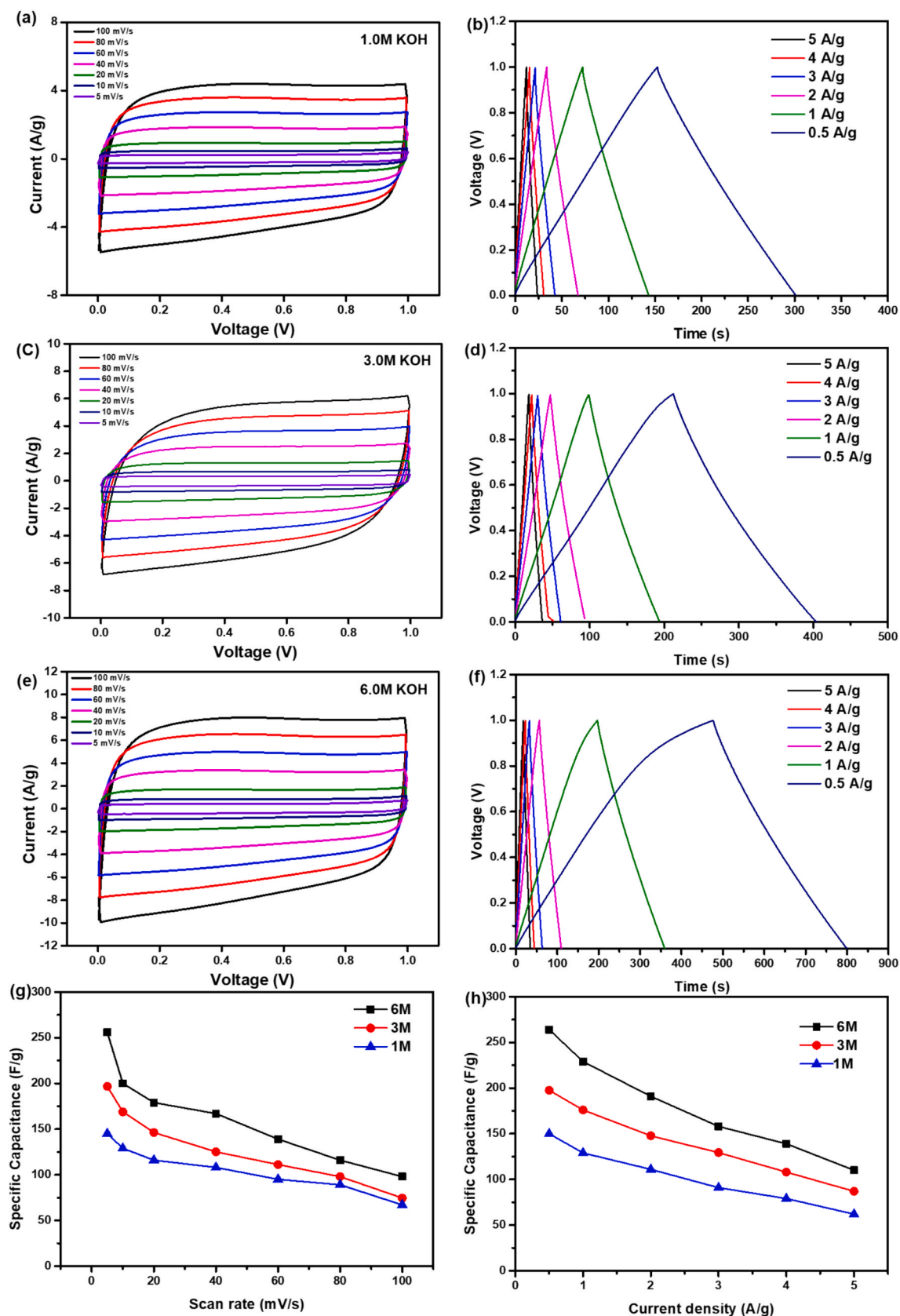


Fig. 6. Electrochemical performance of SLAC electrodes in KOH electrolytes with different concentrations. (a),(c),(e) CV curves at scan rates of 5–100 mV s^{-1} for 1.0 M, 3.0 M, and 6.0 M KOH, respectively. (b),(d),(f) GCD profiles various current densities for 1.0 M, 3.0 M, and 6.0 M KOH, respectively. Variation of specific capacitance with scan rate (g) and with current density (h) in different KOH concentrations.

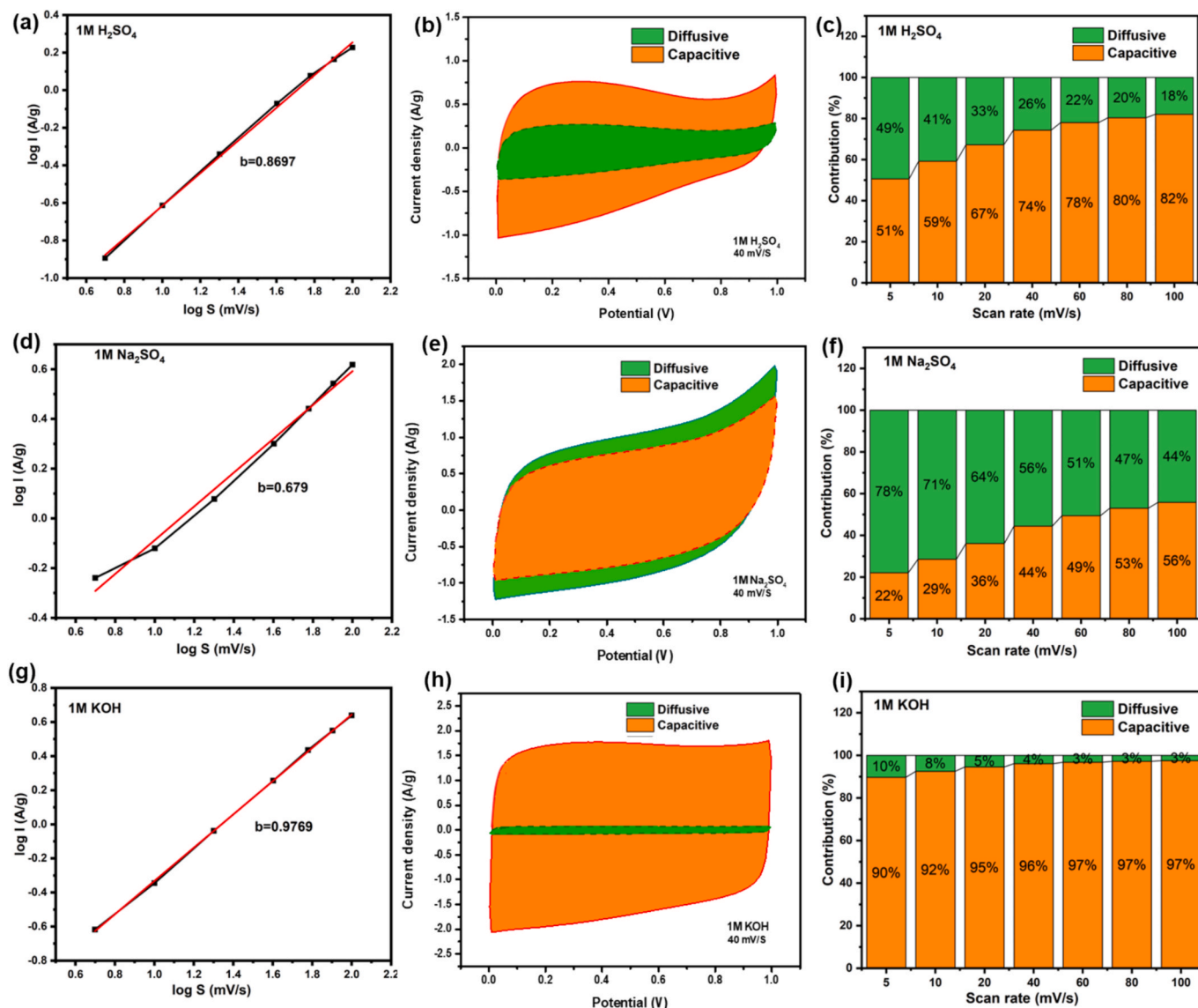


Fig. 7. (a,d,g) $\log(S)$ vs. $\log(I)$ plot for b parameter estimation (b,e,h) capacitive and diffusion contributions of supercapacitor device at 40 mV s^{-1} and (c,f, i) percentage contribution separation of intercalation and capacitive current at the scan rates 5 to 100 mV s^{-1} under the different electrolytes.

accumulation mainly at the electrode surface rather than penetrating the micropores. This leads to a reduction in specific capacitance (Sharma and Chand, 2023). Additionally, the increase in internal resistance and the intensified polarization effect at higher scan rates further contribute to the capacitance reduction. These findings emphasize the limitations of excessively high scan rates, which may adversely impact the performance of supercapacitors in high-power and fast-response applications (Mendhe and Panda, 2023; Ngidi et al., 2024).

The specific capacitance values at 5 mV s^{-1} for 1.0 M, 3.0 M, and 6.0 M KOH were 145, 196, and 254 F g^{-1} , respectively. The observed increase in capacitance with electrolyte concentration is attributed to the higher ionic conductivity and charge transport efficiency, which facilitate improved electrochemical double-layer formation. (Lu et al., 2024). Similarly, a higher electrolyte concentration provides a greater number of available K^+ and OH^- ions, promoting more effective ion adsorption at the electrode surface and leading to an increase in capacitance (Lu et al., 2024; Gajewska et al., 2023). Additionally, at moderate to high concentrations (e.g. 3.0 M and 6.0 M KOH), the electrode material exhibits improved wettability and ion diffusion, ensuring more effective electrochemical double-layer formation and enhanced EDLC behavior. Beyond a certain concentration, excessive ionic strength may lead to ion

aggregation and reduced ion mobility. This can hinder diffusion into the porous electrode structure, ultimately limiting further capacitance gains (Pattanayak et al., 2022). Moreover, the micropores in the SLAC structure contribute to a high specific surface area, providing ample space for charge storage, but their small size may hinder the penetration of larger ions. Meanwhile, mesopores act as ion transport pathways, facilitating ion diffusion into the micropores, reducing internal resistance, and enhancing electrochemical performance. So, the optimized pore size distribution of SLAC ensures effective ion transport, promoting enhanced double-layer capacitance behavior.

Figs. 6(b), 6(d), and 6(f) display GCD curves at 1.0, 3.0, 6.0 M KOH at different discharge current densities from 0.5 to 5 A g^{-1} . All curves have a symmetric triangular shape with negligible iR drops. The GCD curves exhibit a quasi-triangular shape at current densities ranging from 0.5 to 5 A g^{-1} , indicating that the SLAC samples possess supercapacitive properties, making them well-suited for supercapacitor applications. The nearly triangular profile of the curves reflects the electric double-layer capacitance behavior during charge and discharge cycles (Zheng et al., 2015). Furthermore, the slight reduction in internal electrode material resistance at high current densities suggests that the devices retain relatively low resistance. In addition, the GCD curve at 0.5 A g^{-1}

shows a slightly different charging line position. Based on the GCD test results at 0.5 A g^{-1} using varying KOH concentrations (1.0 M, 3.0 M, and 6.0 M), as shown in Fig. 6(h). It was observed that as the KOH concentration increased, the charge curve became slightly curved and deviated from linearity. This effect may be attributed to the higher concentration of OH^- ions at elevated KOH levels, which enhances ionic conductivity and reduces electrolyte resistance. However, at excessively high concentrations (6 M), ion crowding or increased electrolyte viscosity may occur, slowing ion diffusion and potentially causing charge imbalance, leading to the non-linear curve (Gajewska et al., 2023; Sylla et al., 2019). Additionally, silica (SiO_2) is typically present as an inorganic impurity in biomass and does not serve as a source of surface functionalities. Instead, the oxygen-containing functional groups (e.g., $-\text{COOH}$, $-\text{OH}$) that interact with OH^- ions originate from the carbon framework of the synthesized material, not from silica (Phakkhawan et al., 2022; Jain and Tripathi, 2015). This interaction may slightly enhance pseudocapacitance at higher KOH concentrations. In summary, a higher KOH concentration enhances ionic conductivity and reduces electrolyte resistance, allowing ions to diffuse more efficiently into the porous electrode structure, thereby improving charge storage capacity. However, excessively high electrolyte concentrations (e.g., 6 M KOH) can induce ion aggregation and elevated viscosity, impeding ion diffusion and limiting EDLC formation, thereby reducing capacitance. EDLC charge storage fundamentally arises from two coupled mechanisms: (1) electrostatic ion adsorption at the electrode-electrolyte interface, directly contributing to capacitance, and (2) ion diffusion within the internal micropore and mesopore network, enabling access to the electrode's full surface area. While adsorption dominates instantaneous charge storage at low scan rates, diffusion becomes rate-limiting at higher scan rates due to hindered ion mobility in confined pores. Consequently, adsorption governs the intrinsic charge storage capacity, whereas diffusion dictates performance under dynamic conditions, such as high current densities or rapid cycling. This interplay underscores the critical importance of hierarchical porosity and optimal electrolyte selection to simultaneously maximize adsorption efficiency and diffusion kinetics (Brintakis et al., 2019; Kumar et al., 2020; Helseth, 2021).

4.3. Capacitive and diffusive charge storage behaviors in SLAC supercapacitor electrode

Understanding the capacitive and diffusion-driven charge storage mechanisms in SLAC electrodes is essential for evaluating their suitability as supercapacitor materials. Their electrochemical performance is determined by the interplay between electric double-layer capacitance (non-Faradaic) and Faradaic processes (redox reactions), both of which are influenced by electrode porosity and surface functional groups. Analyzing these mechanisms enables the optimization of SLAC electrodes for enhanced power and energy density, advancing their use in energy storage systems. This study investigates the charge storage behavior of SLAC electrodes in three aqueous electrolytes: 1.0 M H_2SO_4 (acidic), 1.0 M Na_2SO_4 (neutral), and 1.0 M KOH (alkaline). The Dunn method was applied to quantify the relative contributions of surface-controlled capacitive processes and bulk diffusion-controlled reactions during charge storage. The relationship between the logarithm of current ($\log I$) and the logarithm of scan rate ($\log v$) obtained from the CV curve is illustrated in Fig. 7(a), (d), and (g). This relationship follows a power law, expressed as (Wanchan et al., 2025):

$$I = aS^b \quad (5)$$

Where S represents the scan rate, I denotes the current, and a and b are variable parameters derived from the slope of $\log v$ versus $\log I$. The b value provides insight into the charge storage mechanism: a value of $b = 1$ indicates surface-controlled charge storage, while $b = 0.5$ suggests diffusion-controlled charge storage kinetics. It was observed that the b -value for H_2SO_4 electrolyte is 0.8697, indicating a balance between

capacitive and diffusive mechanisms. Na_2SO_4 electrolyte has a b -value of 0.6790, suggesting that ion diffusion plays a dominant role. It is seen that the KOH electrolyte has the highest b -value of 0.9769, meaning that the current is primarily controlled by the capacitive mechanism. This mechanism occurs when ions from the electrolyte accumulate at the interface of the SLAC electrode, forming an electrical double-layer capacitance. The charge storage is purely electrostatic with no charge transfer (no redox reactions involved) (Wanchan et al., 2025; Guru Prakash et al., 2019).

To evaluate the diffusive and capacitive behavior of SLAC materials, the following power-fitting relationship is applied (Wanchan et al., 2025).

$$I(v) = k_1 v + k_2 v^{1/2} \quad (6)$$

Where $k_1 v$ and $k_2 v^{1/2}$ denote the contribution of the current resulting from the diffusion and capacitive mechanism, respectively. The values of k_1 and k_2 are determined by the linear fitting of the plot of $\frac{I(v)}{v^{1/2}}$ vs. $v^{1/2}$. Figs. 8(b), (e), and (h) display the CV curves of the SLAC sample at a scan rate of 40 mV s^{-1} in various electrolytes, with capacitive (orange) and diffusive (green) current contributions clearly distinguished. Notably, two of the plots coincide in the figure. Among the electrolytes, H_2SO_4 shows a mixed behavior, involving both capacitive and diffusive mechanisms, while Na_2SO_4 is primarily governed by diffusive processes. In contrast, KOH is characterized by an almost entirely capacitive response. Additionally, the bar graphs illustrate the percentage contributions of capacitive and diffusive processes at various scan rates for each electrolyte, as shown in Figs. 8(c), (f), and (i). In H_2SO_4 , the capacitive contribution rises from 51 % at 5 mVs^{-1} to 82 % at 100 mVs^{-1} . The Na_2SO_4 exhibits predominantly diffusive behavior, especially at lower scan rates, with 78 % diffusive contribution at 5 mVs^{-1} , which gradually decreases as the scan rate increases. Meanwhile, KOH maintains a consistently high capacitive contribution (90–97 %) across all scan rates, highlighting its efficient charge storage and release with minimal diffusion limitations (Kumar et al., 2020; Yahya et al., 2019; Ji et al., 2021). In this study, the shaded area represents the diffusive contribution, while the remainder corresponds to the capacitive contribution. The analysis reveals that, in general, the diffusive contribution is smaller than the capacitive one, reflecting a characteristic feature of supercapacitors where rapid, surface-controlled processes dominate charge storage. However, an interesting deviation is observed in the Na_2SO_4 electrolyte at 40 mV s^{-1} , where the diffusive contribution exceeds the capacitive contribution. This behavior can be attributed to the neutral nature of Na_2SO_4 , which has lower ionic conductivity than acidic or alkaline electrolytes (Rajasekaran et al., 2023). Under these conditions, limited ion transport enhances diffusion-controlled processes, resulting in a greater diffusive contribution. This method of representation and interpretation aligns with observations reported in several previous studies (Su et al., 2020; Başgöz et al., 2025), supporting the consistency of our findings with the established literature.

The results indicate that charge storage in H_2SO_4 and Na_2SO_4 is primarily controlled by ion diffusion, suggesting that their energy storage performance relies on ion transport and pseudocapacitive reactions. On the other hand, KOH exhibits mainly capacitive behavior, allowing for fast charging and discharging through the electric double-layer capacitance mechanism. This difference can be explained by variations in ion size, electrolyte characteristics, and interactions between the electrode and electrolyte.

The smaller size and higher mobility of OH^- ions in KOH, compared to SO_4^{2-} ions in H_2SO_4 and Na_2SO_4 , promote more efficient capacitive charge storage. This is attributed to the enhanced penetration of KOH ions into the porous structure of carbon electrodes, which improves ion accessibility and strengthens electric double-layer capacitance by enabling efficient charge transfer at the electrode-electrolyte interface. Additionally, KOH's compatibility with carbon materials minimizes resistance, further optimizing capacitive behavior. Another key

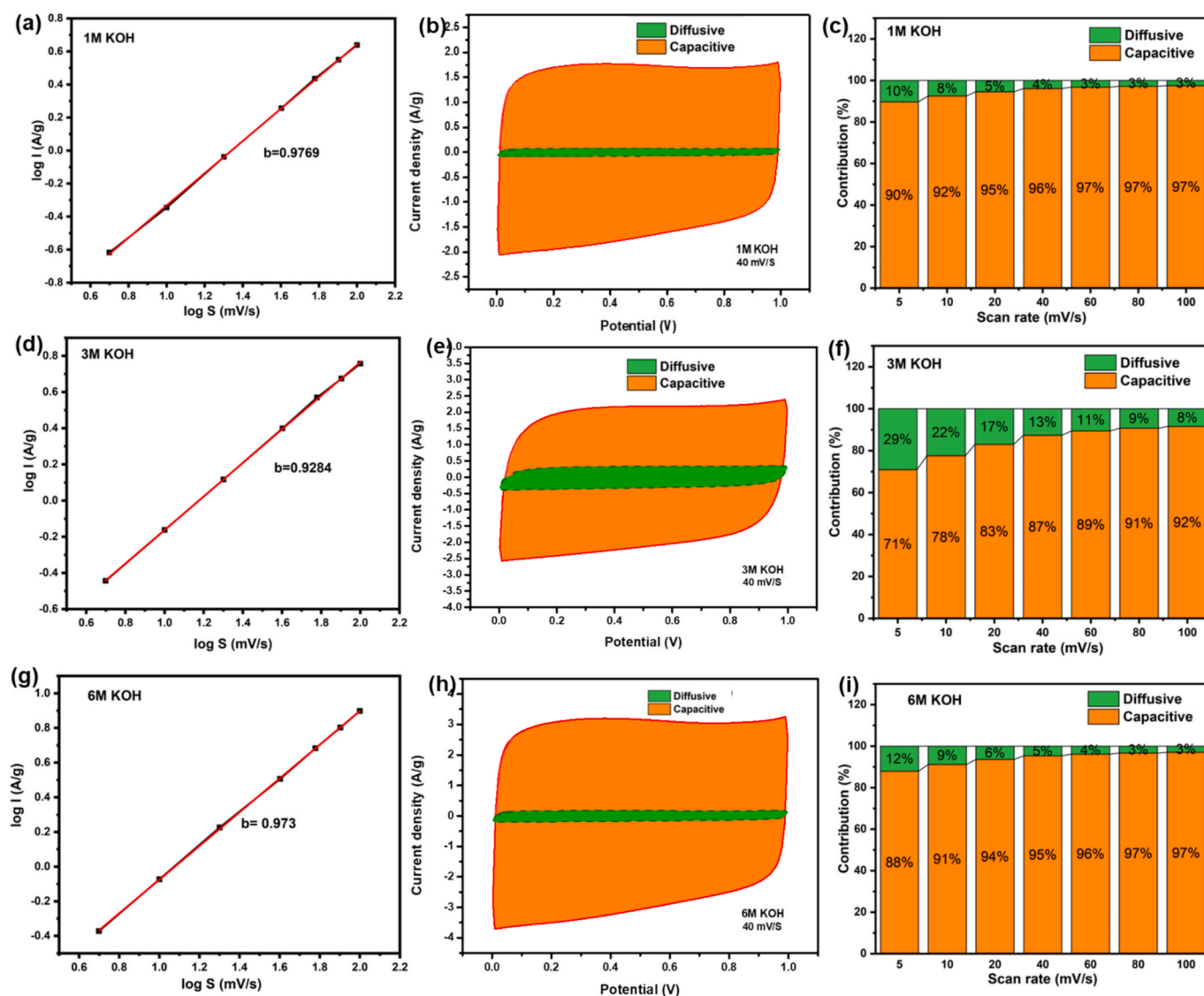


Fig. 8. (a),(d), and (g) $\log(I)$ vs. $\log(S)$ plot for b parameter estimation (b,e,h) Capacitive and diffusion contributions of supercapacitor device at 40 mV s^{-1} and 8(c), (f), and (i) Percentage contribution separation of intercalation and capacitive current at the scan rates 5 to 100 mV s^{-1} under the different KOH concentration.

consideration is the chemical stability of electrodes in different electrolytes. While KOH and Na_2SO_4 are relatively mild, H_2SO_4 's high acidity and corrosive nature can degrade carbon-based electrodes over repeated cycles, leading to structural deterioration and reduced long-term performance in energy storage systems. In contrast, KOH provides superior electrode stability by avoiding the aggressive corrosive effects observed with H_2SO_4 or Na_2SO_4 , making it a more suitable electrolyte for long-term applications. Consequently, the influence of KOH concentration on capacitive and diffusion-controlled charge storage mechanisms was investigated in detail (Xun et al., 2021; Sahu et al., 2023; Pant et al., 2023).

This version clarifies the comparative stability of KOH, specifies the nature of corrosion in acidic/sulfate electrolytes, and emphasizes the systematic study of concentration-dependent charge storage behavior using standard scientific terminology. Figs. 8(a), (d), and (g) show the relationship between the logarithm of current ($\log I$) and the logarithm of scan rate ($\log v$) obtained from the cyclic voltammetry (CV) curves at KOH concentrations of 1.0 M, 3.0 M, and 6.0 M, respectively. These results indicate that the b -value for 1.0 M KOH is 0.9769, suggesting that charge storage is primarily capacitive. When the concentration increases to 3.0 M KOH, the b -value decreases slightly to 0.9284, reflecting a greater influence from ion diffusion-controlled processes. At 6.0 M KOH,

the b -value increases to 0.973, which is close to unity, indicating that capacitive behavior remains dominant even at higher electrolyte concentrations. Figs. 9(b), (e), and (h) present the CV curves at a scan rate of 40 mV s^{-1} for different KOH concentrations. In 1.0 M KOH, charge storage is mainly capacitive with minimal contribution from diffusive processes. At 3.0 M KOH, the diffusive contribution becomes more apparent, though capacitive behavior still dominates. In 6.0 M KOH, capacitive charge storage remains predominant, with a slight decrease in the diffusive component. Figs. 9(c), (f), and (i) display the bar graph percentages of capacitive and diffusive contributions at various scan rates. In 1.0 M KOH, capacitive storage exceeds 90 % at all scan rates, reaching 97 % at 100 mV s^{-1} . In 3.0 M KOH, the capacitive contribution starts at 71 % at 5 mV s^{-1} and increases to 92 % at 100 mV s^{-1} , indicating a greater influence of diffusion at lower scan rates. In 6.0 M KOH, capacitive behavior remains dominant, with the contribution reaching 97 % at higher scan rates, similar to 1.0 M KOH. The findings demonstrate that capacitive charge storage dominates across all KOH concentrations, although slight differences arise depending on electrolyte molarity. Both 1.0 M and 6.0 M KOH maintain consistently high capacitive contributions across all scan rates. In contrast, 3.0 M KOH exhibits more noticeable diffusive effects, especially at lower scan rates. This suggests that ion transport dynamics within the electrolyte shift with increasing

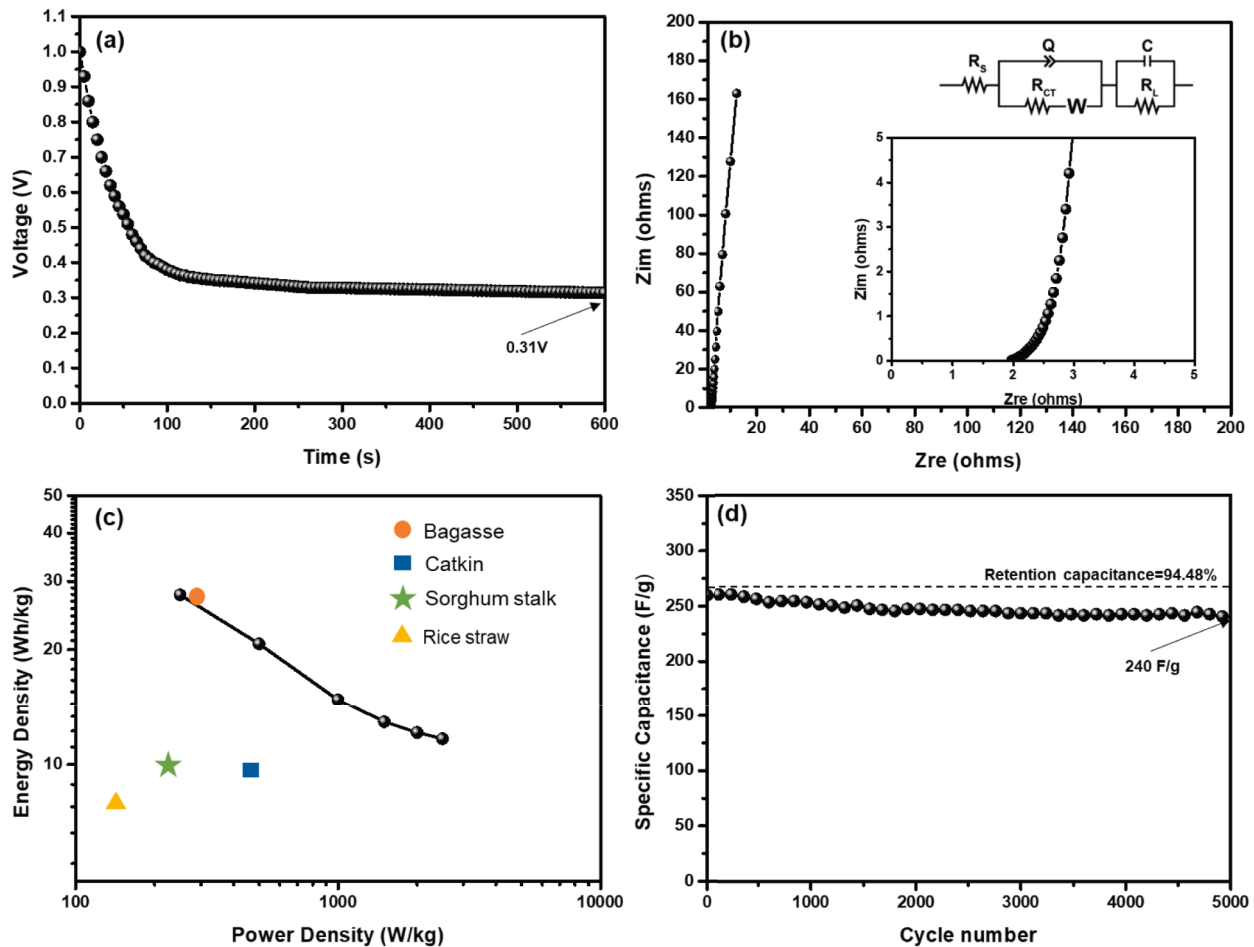


Fig. 9(a) self-discharge (b) Nyquist plots of SLAC (b) stability test (c) Ragone plot and (d) cyclic test of supercapacitor electrode

Fig. 9. (a) self-discharge (b) Nyquist plots of SLAC (b) stability test (c) Ragone plot and (d) cyclic test of supercapacitor electrode.

concentration. At 3.0 M KOH, higher viscosity may restrict ion mobility, increasing the contribution from diffusion. However, at 6.0 M KOH, despite the high concentration, capacitive behavior remains strong, indicating that ion accessibility at the electrode surface is not significantly reduced. These trends may be explained by the behavior of the electrode–electrolyte interface at different electrolyte concentrations. In highly concentrated solutions like 6.0 M KOH, a stronger electric double layer may form, facilitating rapid charge accumulation and offsetting the negative effects of higher viscosity. Conversely, in 1.0 M KOH, high ionic conductivity supports efficient ion transport and capacitive response. The deviation seen at 3.0 M KOH suggests a transition state where increasing viscosity starts to affect charge storage behavior before stabilizing at higher concentrations (Yeetsorn et al., 2020; Sharma and Chand, 2023; Vijeth et al., 2018). From a practical standpoint, these results highlight that supercapacitor performance depends not only on the electrolyte type but also on its optimal concentration. While higher KOH concentrations can improve ion availability, excessive molarity may introduce transport limitations. The similar capacitive behavior observed in 1.0 M and 6.0 M KOH indicates that the system operates efficiently within this concentration range, whereas 3.0 M KOH may present diffusive constraints that slightly reduce capacitive efficiency. Understanding these subtle variations is essential for designing

supercapacitor systems that balance electrolyte concentration with efficient charge storage and transport properties (Yeetsorn et al., 2020; Sharma and Chand, 2023; Jia et al., 2023; Vijeth et al., 2018; Liu et al., 2016; Bi et al., 2022).

To elucidate the influence of electrolyte concentration, the conductivity and viscosity of KOH solutions at 1 M, 3 M, and 6 M were evaluated (Table 3). Among these, 6 M KOH exhibited the highest conductivity ($312 \pm 5 \text{ mS cm}^{-1}$), albeit with increased viscosity ($2.08 \pm 0.07 \text{ mPa}\cdot\text{s}$). This indicates that the elevated concentration of charge carriers at 6 M compensates for the reduced ion mobility associated with higher viscosity, thereby delivering superior ionic conductivity. In contrast, 1 M KOH displayed the lowest viscosity ($1.02 \pm 0.05 \text{ mPa}\cdot\text{s}$) but, due to its limited ion concentration, offered significantly lower conductivity. Consequently, the observed electrochemical performance

Table 3

Measured conductivity and viscosity of KOH electrolytes at 25 °C.

Concentration	Conductivity (mS cm^{-1})	Viscosity ($\text{mPa}\cdot\text{s}$)
1 M	198 ± 3	1.02 ± 0.05
3 M	245 ± 4	1.38 ± 0.06
6 M	312 ± 5	2.08 ± 0.07

reflects this interplay: 6 M KOH promotes efficient charge transport despite viscous resistance, whereas 1 M and 3 M solutions exhibit diminished performance owing to insufficient carrier density or intermediate transport limitations. These findings demonstrate that the optimal electrolyte arises from a balance between ion concentration and mobility. Beyond double-layer charge storage, the pseudocapacitive contribution of SLAC in 6 M KOH is further enhanced by reversible redox reactions of oxygenated surface functionalities, including quinone/hydroquinone groups, phenolic $-OH$, and carbonyl moieties. These active sites interact with OH^- ions in the alkaline medium, thereby augmenting the overall charge storage capacity.

In alkaline electrolyte (6 M KOH), the pseudocapacitance contribution of SLAC arises from the faradaic redox reactions of surface oxygen-containing functional groups (Leppanen et al., 2022). In particular, quinone moieties can reversibly undergo redox transformation to hydroquinone species ($C=O + 2e^- + 2OH^- \leftrightarrow C-(OH)_2$), thereby contributing to charge storage beyond the electrical double-layer mechanism. Additionally, phenolic and carbonyl functionalities may also participate in similar surface redox processes, leading to enhanced capacitance. These reversible redox reactions at the electrode-electrolyte interface are responsible for the higher pseudocapacitive contribution observed in concentrated KOH electrolyte (Liu et al., 2020).

4.4. Performance evaluation of SLAC electrode supercapacitor

Fig. 9(a) presents the self-discharge behavior of the SLAC supercapacitor. Under open-circuit conditions, the voltage decreases continuously, a phenomenon typical of EDLCs that directly affects long-term energy retention. The voltage-time profile shows an initial potential of 1.0 V, followed by a rapid drop that transitions into a slower decay, stabilizing at 0.3 V within 600 s during a single test cycle. This two-stage decay reflects EDLC behavior, where charge storage relies on electrostatic adsorption at the electrode-electrolyte interface. Key contributors to this discharge include: (i) charge redistribution across the porous carbon network, (ii) ion diffusion limitations in the concentrated electrolyte, and (iii) leakage currents resulting from parasitic processes (Ngidi et al., 2024; Shahcheragh et al., 2023). The time constant derived from the voltage decay indicates $\sim 69\%$ potential loss during the test period, underscoring the discharge kinetics of the sugarcane leaf-derived electrode. In addition, our work further evaluated the leakage current behavior of sugarcane leaf-derived activated carbon electrodes. The leakage current was calculated from the self-discharge voltage time relationship (Lewandowski et al., 2013), and a value of 2.479 mA at 1.0 V was obtained. This is substantially lower than the values reported for certain organic electrolytes in the literature. For instance, Kötzt et al. (Kötzt et al., 2008) observed that while TEABF₄/propylene carbonate exhibited the lowest leakage current (5.3 mA), other solvents such as TEABF₄/GBL reached as high as 23.3 mA. Our results demonstrate that the optimized structure of sugarcane leaf-derived carbon effectively reduces leakage current, confirming its promise as a stable supercapacitor electrode material. (Liu et al., 2021).

EIS was used to examine the charge transfer properties, ion diffusion behavior, and overall impedance of the SLAC electrode material (Ngidi et al., 2024; Shahcheragh et al., 2023; Umezawa et al., 2021; Taer et al., 2023). Fig. 9(b) shows the Nyquist plot of the SLAC electrode with the highest performance, tested in 6.0 M KOH over a frequency range of 10 mHz to 100 kHz. The results reveal clear supercapacitor behavior, demonstrated by a low equivalent series resistance (ESR) of 1.8 Ω , which reflects the excellent electrical conductivity of both the electrode material and the highly conductive 6 M KOH electrolyte. Moreover, the charge transfer resistance (R_{ct}) is remarkably low at 1.0 Ω , indicating efficient electrochemical reactions supported by the well-developed pore structure of the electrode. This structure enhances rapid ion transport and charge redistribution at the electrode-electrolyte interface. In the low-frequency region, the Nyquist plot shows a nearly

vertical line relative to the Z' axis, which is characteristic of strong capacitive behavior and stable energy storage capacity. This pattern confirms that charge storage and release occur through a combination of electric double-layer capacitance and pseudocapacitance mechanisms, highlighting the material's excellent charge storage capability with minimal diffusion resistance. The porous structure of activated carbon derived from sugarcane leaves significantly improves ion diffusion within the electrolyte, reducing charge diffusion barriers and enhancing overall electrode efficiency (Lakshmi and Vedhanarayanan, 2023; Nicolson et al., 2020).

Equivalent circuit analysis demonstrates that 6.0 M KOH electrolyte significantly influences the electrochemical properties of the sugarcane leaf-derived activated carbon (SLAC) electrode. The electrolyte's low resistivity lowers the solution resistance (R_s), as the high ionic conductivity of OH^- ions enables efficient charge transfer across the system. However, a Warburg impedance value of 0.09 Ω indicates restricted OH^- ion diffusion within the electrode's pores. This may arise from non-uniform pore sizes or residual activation byproducts obstructing pores, thereby limiting ion mobility. Additionally, a minimal leakage resistance ($R_L = 0.002 \Omega$) reflects low charge loss, though structural optimization could further reduce this parameter. While the SLAC electrode displays strong electric double-layer capacitance, performance improvements are achievable through targeted modifications. Enhancing porosity via controlled activation or templating methods could enhance ion mobility and mitigate Warburg impedance. Surface treatments, such as nitrogen doping, may improve charge transfer kinetics and electrochemical stability. Furthermore, optimizing post-activation washing to eliminate residual byproducts would maximize pore availability and reduce diffusion resistance. These refinements could advance the SLAC electrode's suitability for high-performance supercapacitors in energy storage technologies (Jain and Tripathi, 2015). Equivalent circuit analysis demonstrated a low charge transfer resistance ($R_{ct} = 1.0 \Omega$), confirming favorable electrochemical kinetics. In addition, the measured Warburg impedance (0.09 Ω) reflected moderate OH^- diffusion constraints, which can be attributed to pore non-uniformity and residual byproducts from activation. The extremely low leakage resistance ($R_L = 0.002 \Omega$) further evidenced minimal charge loss during operation. Collectively, these results offer complementary kinetic insights beyond those obtained from Dunn's method, underscoring the efficient ion transport characteristics of SLAC while also indicating that further pore optimization could alleviate remaining diffusion limitations.

The Ragone plot (Fig. 9(c)) illustrates the relationship between energy density and power density for the SLAC electrode. The electrode achieves a maximum energy density of 27.70 Wh/kg at 0.5 A/g, which is competitive with commercial EDLCs. It also delivers a peak power density of 250 W/kg, highlighting its potential for high-power applications. Additionally, the SLAC electrode maintains a relatively high energy density even at higher current densities, demonstrating good rate capability. This performance can be attributed to its well-developed porous structure, which enhances ion diffusion and electrical conductivity. Compared to biomass-derived activated carbon materials reported in the literature (Okonkwo et al., 2021; Jain and Tripathi, 2015; Hodgson-Kratky et al., 2019; Said et al., 2023; Barakat et al., 2024), the SLAC electrode shows a favorable balance between energy and power density, making it a strong candidate for supercapacitor applications. Furthermore, to assess the practical applicability, a Ragone plot was constructed and compared with both commercial EDLC benchmarks such as coconut shell-derived activated carbons and other biomass-derived carbons (catkins (Ma et al., 2015), rice straw (Sudhan et al., 2017), sorghum stalk (Ma et al., 2016), and bagasse (Mohit and Hashmi, 2022)). The results confirm that SLAC delivers superior energy-power characteristics compared with these biomass-based carbons and competitive performance relative to commercial benchmarks, highlighting its strong potential for real-world deployment. Nevertheless, the use of concentrated alkaline electrolytes (6 M KOH) raises challenges

related to electrolyte leakage and device scalability. These risks must be carefully managed in device engineering, and future studies will focus on optimizing device design and exploring alternative electrolytes to enhance safety and large-scale applicability. Fig. 9(d) shows the cyclic stability test over 5,000 cycles at a current density of 0.5 A/g. The SLAC electrode exhibits excellent electrochemical stability, retaining 94.46 % of its capacitance after 5000 charge–discharge cycles, indicating minimal degradation and high charge reversibility. This remarkable cyclic performance can be attributed to the well-developed porous structure of SLAC, which supports efficient electrolyte ion diffusion throughout the electrode material. The interconnected network of mesopores and micropores enhances ion transport and ensures uniform charge distribution, preventing localized degradation and maintaining capacitance over extended cycling (Bi et al., 2022; Butcha et al., 2023). Furthermore, the structural integrity of SLAC minimizes pore collapse and electrode deterioration, making it a highly promising material for supercapacitor electrodes in long-term energy storage applications. These characteristics make SLAC a strong candidate for industrial-scale supercapacitor development, especially for energy storage systems requiring long-term durability and stable electrochemical performance over thousands of cycles. This study distinguishes itself by investigating carbon derived from sugarcane leaves, an underexplored precursor for supercapacitor electrodes. Unlike prior research, which predominantly concentrated on sugarcane bagasse as a carbon source, this work highlights sugarcane leaves as a sustainable and underutilized alternative (Sattayarat et al., 2019). The findings underscore the viability of sugarcane leaf-derived carbon, showcasing comparable electrochemical performance to conventional carbon materials while achieving enhanced specific capacitance and cycling stability, as benchmarked against existing studies (Table 4). These results broaden the applicability of biomass-derived carbons in energy storage, proposing a promising direction for designing eco-efficient supercapacitors with high performance (Rajasekaran et al., 2023; Liu et al., 2022). Compared with heteroatom-doped carbons, such as N/O-co doped longan shell carbon (Lee et al., 2021) and B/N-co doped β -cyclodextrin carbon (Yang et al.), which exhibit enhanced capacitance owing to synergistic heteroatom doping effects, the SLAC electrode demonstrates a slightly lower capacitance. However, it is noteworthy that SLAC achieves superior cycling stability

(94.48 % capacitance retention after 5,000 cycles) without the need for additional doping steps. Moreover, the sugarcane leaf precursor is abundantly available and cost-free as an agricultural by-product, highlighting the cost-effectiveness and sustainability of this approach. Therefore, while doped carbons excel in maximizing charge storage, SLAC provides a competitive balance between electrochemical performance, durability, and economic feasibility, making it a promising candidate for practical and scalable supercapacitor application. It is important to note that the current cyclic stability assessment was restricted to 5,000 cycles owing to instrumental limitations. In future studies, the cycling evaluation will be extended beyond 10,000 cycles, consistent with reports on heteroatom-doped carbons, to more rigorously verify the long-term durability and practical applicability of SLAC. Correlating pore characteristics and surface chemistry with electrochemical measurements reveals that the mesoporous structure in SLAC enhances electrolyte diffusion and reduces ion-transport resistance, as reflected by the lower ESR values in EIS. Meanwhile, surface oxygen functionalities contribute to the additional capacitance observed beyond the EDLC contribution, consistent with the redox features in CV. These results confirm that the optimized pore structure and functional groups of SLAC synergistically improve capacitance, rate capability, and cycling stability.

Fig. 10 illustrates the charge storage mechanism in activated carbon-based supercapacitors, where electrolyte ions migrate toward the oppositely charged electrode and form an electric double layer without involving faradaic reactions. Upon applying a potential, counter-ions initially adsorb onto the external surface of the carbon material and subsequently diffuse through mesopores into micropores, where the majority of charge storage occurs (Jain and Tripathi, 2015; Chae et al., 2021). Micropores contribute a large specific surface area essential for high capacitance, while mesopores serve as ion transport pathways that reduce diffusion resistance and enhance rate capability (Guan et al., 2025). At high scan rates, restricted ion diffusion into micropores becomes the rate-limiting factor, resulting in partial utilization of the internal surface area and reduced capacitance. Therefore, an optimized hierarchical pore structure, combining micropores for efficient charge storage and mesopores for rapid ion transport, is critical to achieving balanced energy and power performance (Ngidi et al., 2024). Additionally, electrolyte characteristics such as ionic size and mobility play a significant role in governing ion adsorption and diffusion behavior. These findings underscore the importance of aligning electrode architecture with appropriate electrolyte selection to ensure high efficiency, rate performance, and long-term stability in supercapacitor systems. When compared with other biomass-derived heteroatom-doped carbons, such as N/O-co doped longan shell, B/N-codoped β -cyclodextrin, and N/B dual-doped porous carbons, SLAC exhibits a comparatively lower capacitance. Nevertheless, its outstanding cycling stability (94.48 % retention after 5,000 cycles), combined with the low-cost and abundant sugarcane leaf precursor, underscores its strong potential as a competitive and sustainable electrode material for supercapacitor applications (Yang et al., 2025).

5. Conclusion

This study successfully establishes SLAC as a high-performance, sustainable electrode material for supercapacitors. We addressed key challenges in biomass-derived carbons by optimizing a synthesis route combining HTC (240 °C) of waste sugarcane leaves with subsequent chemical activation using K_2CO_3 (800 °C). This process yielded SLAC with an exceptionally high specific surface area (2006.91 m² g⁻¹) and a critically balanced hierarchical porous structure comprising 39 % micropores and 61 % mesopores. Structural characterization revealed a beneficial combination of graphitic domains (Id/Ig = 0.54), ensuring excellent electrical conductivity and stability, alongside amorphous carbon. This deliberative structural engineering, achieving high surface area, optimal pore size distribution for ion transport, and enhanced

Table 4
Benchmarking carbon-derived electrodes for SC: key electrochemical performance.

Electrode samples	Electrolyte	Specific capacitance (F g ⁻¹)	Retention capacity (%) at Cyclic Stability (cycles)	Ref
Sugarcane bagasse	GPE (PVdF-HFP/ EMITf/ NaTf)	193 at 1.0 A g ⁻¹ 215 at 0.5 A g ⁻¹	92.00 % at 10,000	(Mohit and Hashmi, 2022)
Sugarcane bagasse	[PVdF(HFP) EMIM(Br)] [PC-Mg (ClO ₄) ₂]	248 at 0.5 A g ⁻¹	—	(Jain and Tripathi, 2015)
Sugarcane bagasse	6.0 M KOH	314 at 9.0 A g ⁻¹	96.00 % at 20,000	(Okonkwo et al., 2021)
Sugarcane bagasse	2.0 M KOH	265 at 0.2 A g ⁻¹	98.63 % at 15,000	(Sarkar et al., 2020)
Sugarcane bagasse	6.0 M KOH	259 at 0.5 A g ⁻¹	89.60 % at 5,000	(Wei et al., 2021)
Sugarcane bagasse	6.0 M KOH	138.61 at 0.5 A g ⁻¹	100 % at 1,000	(Phakkhawan et al., 2022)
Longan shell	1 M M H ₂ SO ₄	272F g ⁻¹ 0.5 A g ⁻¹	95.70 % at 5,000	(Yang et al., 2025)
Coconut Shell	6 M LiNO ₃	88F g ⁻¹ at 1 A g ⁻¹	92.00 % at 5,000	(Lee et al., 2021)
Sugarcane leaves	6.0 M KOH	254 at 0.5 A g ⁻¹	94.48 % at 5,000	This work

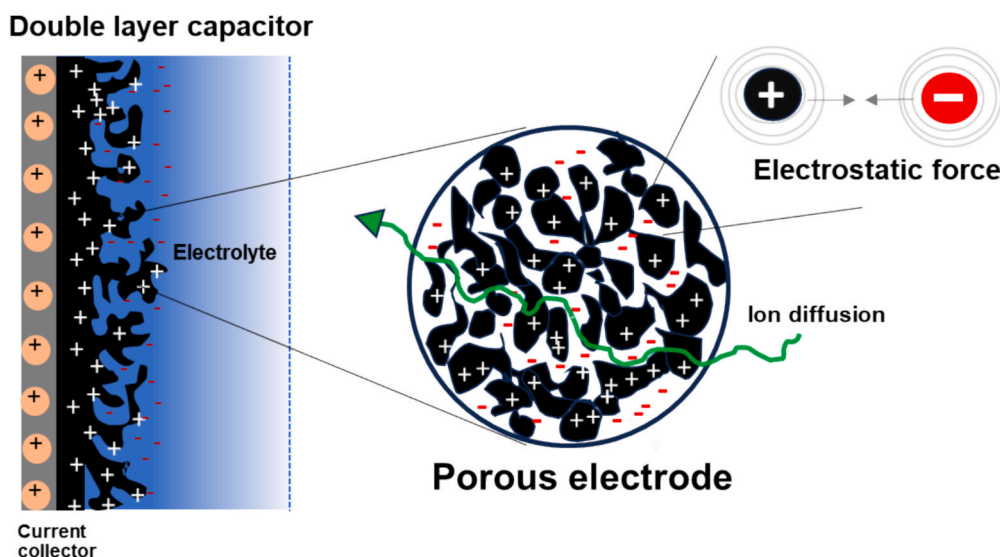


Fig. 10. Charge storage mechanism of activated carbon in supercapacitors.

conductivity, directly addresses common limitations of biomass carbons related to conductivity, pore accessibility, and scalability, representing a significant advancement in sustainable electrode design. The resultant SLAC electrodes delivered outstanding electrochemical performance, particularly in 6.0 M KOH electrolyte, achieving a high specific capacitance of 254 F g^{-1} at 0.5 A g^{-1} . This superior performance is attributed to the synergistic effects of the hierarchical porosity facilitating rapid ion diffusion (especially by smaller K^+/OH^- ions) and the material's high conductivity, confirmed by low equivalent series resistance (1.8Ω) and charge transfer resistance (1.0Ω). Charge storage analysis revealed a predominantly capacitive mechanism (90–97 %), ensuring fast kinetics and excellent rate capability, further evidenced by high capacitance retention (94.48 % after 5,000 cycles). Furthermore, SLAC demonstrated promising energy and power densities (27.70 Wh kg^{-1} and 250 W kg^{-1} , respectively). Dunn analysis and self-discharge tests confirmed efficient, diffusion-minimized EDLC behavior and reliable charge retention. This work not only demonstrates the viability of SLAC as a next-generation supercapacitor electrode combining high capacitance, remarkable stability, and superior power handling but also provides fundamental insights into the critical interplay between hierarchical porosity, electrolyte selection, and ion dynamics for optimizing charge storage in sustainable carbons.

CRedit authorship contribution statement

Waritnan Wanchan: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Rungsima Yeetsorn:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition. **Sanchai Kuboon:** Supervision, Investigation. **Gaurav Kumar Yogesh:** Validation, Software, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research has received funding support from the NSRF via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation [grant number B13F680073]. Additional funding was provided by King Mongkut's University of

Technology North Bangkok and the National Science and Technology Development Agency, Thailand (Contract no. Grad 004/2564).

Data availability

No data was used for the research described in the article.

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