

Flash joule heating synthesis of porous graphene oxide from banana leaf waste for high-performance supercapacitor electrodes

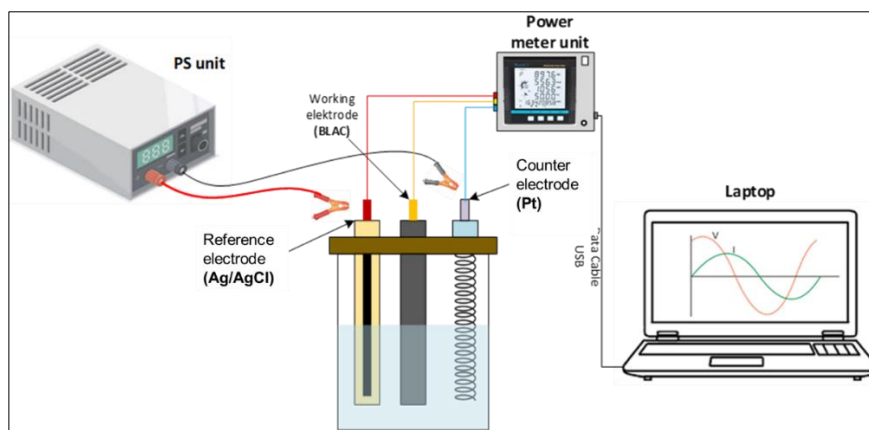
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Highlights:

- Utilization of banana leaf waste as a sustainable biomass source for supercapacitor electrodes.
- Graphene oxide synthesized using the ultrafast Flash Joule Heating method.
- Characterization confirmed porous structure with oxygen-rich functional groups enhancing electrochemical performance.
- Voltage variation showed that moderate conditions yield the best structure, conductivity, and stability.
- This study demonstrates an innovative and eco-friendly approach to future energy storage materials.

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Abstract

This study investigates the synthesis of porous graphene oxide (GO) derived from banana leaf waste using the Flash Joule Heating (FJH) method for supercapacitor electrode applications. Carbonization was conducted at input voltages of 5, 10, and 15 VA for 2 s, followed by activation with 0.3 M KOH. Structural characterization (SEM, EDX, FTIR, and XRD) confirmed the formation of hierarchical porous carbon with oxygen-containing functional groups. Electrochemical evaluation revealed that the sample synthesized at 10 VA exhibited the best performance, achieving a specific capacitance of 345 F g⁻¹, low internal resistance of 0.65 Ω, and capacitance retention of 95% after 500 cycles. In contrast, the 5 VA sample showed lower conductivity due to its amorphous structure, while the 15 VA sample exhibited reduced capacitance due to excessive macropore formation. These results demonstrate that controlled FJH voltage plays a critical role in optimizing pore structure and electrochemical performance, highlighting banana leaf-derived GO as a promising and sustainable electrode material for high-performance supercapacitors.

Keywords: Graphene oxide; Flash joule heating; Banana leaf; Electrode; Supercapacitor

1. Introduction

Currently, global energy consumption has increased significantly. To address the growing dependence on fossil fuels, the development of rechargeable energy storage devices with low cost [1], environmental friendliness, high capacity, and stable physicochemical properties has become increasingly important [2]. Supercapacitors (SCs) are one energy storage technology that has attracted much attention recently. SCs are devices that combine the advantages of conventional capacitors and rechargeable batteries [2], [3], [4]. This technology offers advantages such as a longer lifespan [5], [6], a simple working system [7], [8], fast charging, and high power density [9], [10]. SC applications are widely used in hybrid electric vehicles [11], standby power systems, and telecommunication devices [12]. However, the performance of supercapacitors is strongly influenced by the properties of the electrode materials used. Electrodes commonly used for supercapacitors come from non-renewable carbon sources like graphite. The availability of these materials poses a long-term problem for the development of batteries and supercapacitors [13].

Supercapacitors can be divided into two main types: electric double-layer capacitance (EDLC) and pseudocapacitance, distinguished by their charge storage mechanisms [14]. In EDLC, ions are adsorbed through electrostatic interactions on the surface of the active material, while pseudocapacitance involves redox reaction mechanisms, ion intercalation or extraction, and deposition at low voltage [15], [16]. Both require materials with good chemical and structural stability, high conductivity, and large specific surface area. Therefore, the development of electrode materials with low cost, flexible composition, and microstructural engineering, particularly pore design, is crucial for enhancing the capacity and performance of supercapacitors.

GO is a graphite sheet with sp^2 hybridization, possessing very lightweight properties [17], [18]. This material has potential as a supercapacitor electrode, supported by its superior properties such as good thermal and electrical conductivity, large active surface area, and high chemical stability [19]. However, conventional sources and synthesis methods of GO are often energy-intensive and rely on non-renewable precursors. GO can be synthesized from various sources, one of which is biomass from banana leaf [20]. Banana leaf are an abundant agricultural byproduct in tropical regions. Some sources mention that about 480 kg of leaves are produced for every ton of fruit harvested [21]. Proper utilization of this agricultural byproduct can help reduce environmental problems and enhance sustainability in various industries [22].

Banana leaf contain cellulose, hemicellulose, and lignin ranging from 26% to 54%. Cellulose and hemicellulose provide strength and structure, along with a cuticle for protection [23]. Meanwhile, the lignin content in banana leaf can reach 11-25%, tending to be lower compared to biomass like straw and husks, making it suitable for bioenergy and biomaterial industries that require easily degradable and faster decomposing raw materials [24]. Furthermore, banana leaf contain a significant amount of phenolic compounds, such as ferulic acid and vanillic acid, as well as volatile solids and other trace elements that contribute to water absorption and adsorbent properties [25]. Based on previous research, activated carbon from banana leaf material has magnetic and electric potential in its aromatic rings, which can enhance hydrogen production in water electrolysis [20]. These characteristics indicate that banana leaf biomass is a promising precursor for porous carbon materials with potential electrochemical applications.

Graphene encompasses various carbon allotropes, including activated carbon, graphene, carbon nanotubes, and carbon nanodots [26]. Carbon nanodots, as amorphous precursors, have gained significant interest due to their simple and tunable synthesis process, which can be easily modified for specific applications [26], [27]. During carbonization, lignin acts as the main precursor for biochar with high aromatic groups [28], [29]. The lignin content determines the level of electron activity in the pore structure [30], [31]. Cellulose-rich biomass is beneficial for the formation of graphitic biochar [32], [33]. Intrinsically, the surface area and porosity of biochar play crucial roles in electrochemical processes within energy storage systems. This reason makes carbon from banana leaf an ideal candidate for direct application in supercapacitor electrodes. Thus, carbon derived from banana leaf has strong potential for direct application in supercapacitor electrodes.

One important process in graphite synthesis is the exfoliation of GO sheets into thinner layers [32]. Thinner GO sheets will enhance more effective electrical charge storage capacity [34]. However, excessive thinning and defect formation may also reduce electrical conductivity due to disruption of the graphitic network. The use of conventional carbonization-activation methods often only yields carbon materials with relatively low electrical conductivity [35]. The use of carbonization parameters such as temperature, heating rate, and carbonization time shows significant variation in pore distribution, defect density, and graphene layer size and number.

Defects in graphene layers, arising from imperfect biomass carbonization processes, can affect electrode performance by increasing the active surface area but also decreasing electrical conductivity [36], [37]. Activation using alkali metal doping methods is often chosen to enhance graphene performance [38]. This method, of course, results in increased time and production costs. Therefore, alternative rapid and efficient synthesis methods are required to overcome these limitations.

Ultrafast carbonization using Flash Joule Heating (FJH) has become one of the trending methods for graphene synthesis today. This method involves applying short-duration high-current pulses to carbon-rich materials, raising their temperature to 3000 K [39]. Variations in voltage, pulse duration, and electric current serve as controls for the degree of graphitization, surface area, and oxygen group content in the FJH-derived material [40]. Changes in FJH voltage can enhance aromatic monomers [41], where aromatic groups become ideal precursors for carbon materials [42]. Furthermore, the FJH method can convert the complex lignin structure of the material into graphene with relatively low defects and a turbostratic structure that supports rapid exfoliation [39], [40], [43], [44]. These advantages make FJH a promising approach for producing high-performance carbon materials in a short processing time.

This study investigates the characteristics of flash lignin from banana leaf under flash Joule heating (FJH) at different voltages. Although the FJH method has been successfully used to synthesize various carbon sources from different biomass [40], the utilization of banana leaf waste biomass as an alternative supercapacitor electrode has not been extensively researched, particularly using the FJH method. Therefore, this study aims to systematically evaluate the effect of FJH voltage on the structural, chemical, and electrochemical properties of banana leaf-derived carbon. Besides its potential as an abundant material source, this research is also part of an effort to address various weaknesses of biomass-based electrode materials deemed suboptimal compared to lithium-based materials. The novelty of this work lies in the integration of banana leaf biomass with ultrafast FJH processing and the identification of optimal operating conditions to enhance supercapacitor performance. Based on this, opportunities for perfecting biomass-based supercapacitor electrode materials remain wide open for research and offer solutions to important unresolved issues.

2. Methods

2.1. Material Preparation

Banana leaves specimens were obtained from waste from banana plantations in Banyuwangi City, of the Cavendish variety (*Musa acuminata*). The next stage involved cleaning and drying the banana leaf until a moisture content of $\pm 6\%$ was achieved. This was followed by grinding and meshing processes to obtain 200 grams of biomass powder with a size range of ≤ 74 microns. The carbonization process used a VIV TEK brand 6x33000 μ F (~ 200 mF) FJH reactor. The carbonization process was controlled using input voltages of 5 VA, 10 VA, and 15 VA, each with a treatment time of 2 seconds. Each resulting banana leaf carbon powder was then activated using 0.3 M KOH to reduce impurities on the surface area. Subsequently, the carbon powder was washed with deionized water until the pH reached 7, then dried at 90 °C for 6 hours. The resulting product is Banana Leaf Active Carbon, referred to as BLAC.

2.2. BLAC Material Characterization

BLAC material characterization was conducted through three main analytical approaches to validate its electrode performance. FTIR and EDX were used to identify elemental composition, XRD was applied to examine the crystalline structure, and SEM was utilized to observe surface morphology. FTIR measurements were performed with a Shimadzu IRPrestige-21 instrument in absorption mode. For crystallographic analysis, a PanAnalytical E'Xpert Pro diffractometer with Bragg-Brentano configuration was used, employing a Cu K α radiation source ($\lambda = 1.5405$ Å) with a Ni K β filter. The diffraction measurement range covered 2θ angles from 10° to 90° with a step size of 0.001° and a counting time of 0.7 seconds per point, using a fixed divergent slit of 1.52 mm and a receiving slit of 0.10 mm. An FEI Inspect-S50 electron microscope operated under low vacuum conditions with secondary electron detection produced morphological images and elemental composition data at a magnification of 10 micrometers.

2.3. Collector Sheet Coating

The fabrication of the BLAC electrode used pure aluminum (Al) plates (0.8 mm thick, 4×7 cm in area) as the base material, as Al sheet plates offer advantages in enhancing the contact between the current collector and the active material at the interface [45]. The Al plates were cut to size and coated with a polyurethane-based adhesive. Approximately 20 g of BLAC material was then applied uniformly onto the aluminum surface layer by layer. 20 grams of each BLAC substrate were applied evenly onto the aluminum sheet surface layer by layer. The coated Al sheets 30°C for 12 h. After drying, the electrodes underwent mechanical exfoliation to obtain a thinner and more uniform coating layer.

2.4. Experimental Setup

The performance measurement of the BLAC electrode used a three-electrode electrochemical system consisting of a working electrode made of BLAC, a reference electrode made of Ag/AgCl, and a counter electrode made of platinum, connected to a laptop via an Arduino Uno R3 microcontroller integrated into a potentiostat test unit. The electrodes were placed embedded in a jar lid, with 12 cm inside the jar and 3 cm outside. The experimental equipment was arranged as shown in Figure 1. The gas headspace was 600 ml, while the electrochemical cell was filled with 1M Na_2SO_4 electrolyte as an ionic conduction medium with a volume of 600 ml. The power source used a 12V battery connected to the electrodes with alligator clips and was charged for 10 minutes using a DC-to-DC power supply, then the generated current and voltage were measured to evaluate electrode performance. The entire setup was designed to test the performance of the BLAC electrode in supercapacitor applications, with parameters such as capacitance and stability measured through an Arduino-based interface or a standard electrochemical measurement system.

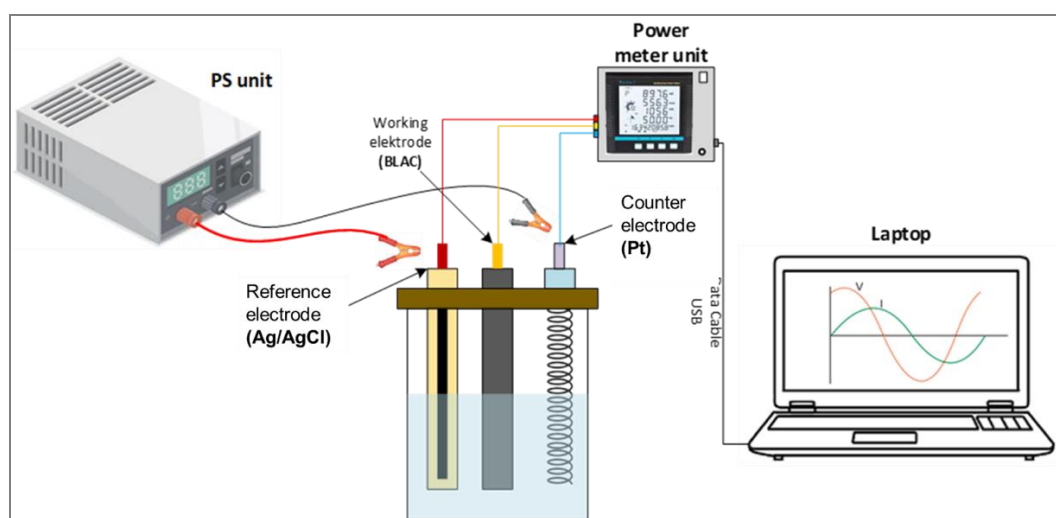


Figure 1.
BLAC electrode
testing installation

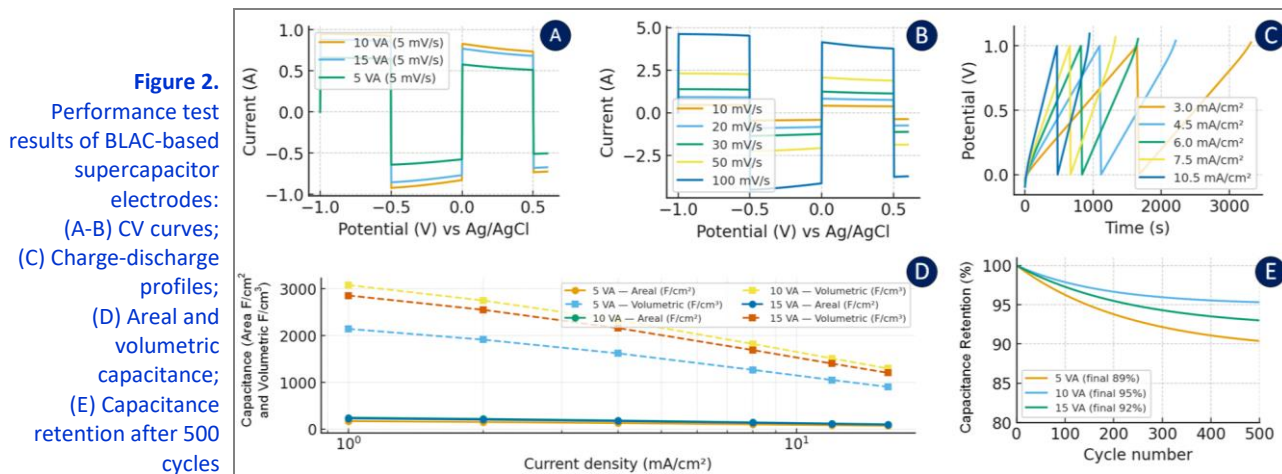
3. Results and Discussion

3.1. BLAC Performance Patterns

The research results demonstrate that variations in FJH voltage significantly influence the performance of BLAC-based supercapacitor electrodes. Distinct response patterns were observed among samples subjected to different treatments, as shown in Figure 2. In Figure 2.a and Figure 2.b, the Cyclic Voltammetry (CV) curves reveal that the electrode at 10 VA voltage exhibits the highest current and the most ideal rectangular shape, indicating the best capacitive response and the lowest internal resistance. This is also reflected in the charge-discharge results (Figure 2.c), where the 10 VA sample maintains a larger capacity at higher currents, demonstrating optimal ion and electron transport efficiency. Figure 2.d presents a comparison of areal and volumetric capacitance values at different current densities. The highest specific capacitance is achieved by the 10 VA sample, both areally and volumetrically, and it also shows a slower decrease in capacitance compared to 5 VA and 15 VA samples as the current density increases. The 5 VA electrode exhibits poor performance due to a carbon structure that is still relatively amorphous and less conductive,

whereas the 15 VA electrode, despite having relatively low resistance, suffers from excessive macropore formation that reduces the effective active surface area [46].

In the cycling stability test (Figure 2.e), the 10 VA BLAC electrode also demonstrates the best capacitance retention (95% after 500 cycles), confirming the structural stability and robustness of sp² bonding as well as the optimal distribution of oxygen-containing functional groups. This result is consistent with the SEM observations showing a well-developed hierarchical pore structure, the EDX analysis indicating balanced carbon-oxygen composition, and the FTIR results confirming the presence of stable functional groups. The 5 VA electrode declines more rapidly (89% retention), indicating structural degradation due to a more amorphous carbon network. This is supported by its less ordered morphology and lower graphitization observed in SEM and XRD results. Conversely, the 15 VA electrode is slightly more stable (92%) but still underperforms compared to the 10 VA sample, highlighting the importance of balancing crystallinity, micro-mesoporous porosity, and controlled defects, which will be further discussed in the SEM-EDX, FTIR, and XRD analysis results.



3.2. The Effect of FJH Voltage on the Performance of the BLAC Electrode

SEM imaging was performed to analyze the morphology of BLAC. SEM images at 20 μ m magnification showing the original form of BLAC and graphite flakes are shown in Figure 3. The BLAC specimen from FJH at 5 VA shows a predominantly amorphous structure with relatively small and irregular micro-pore distribution. Crystal formation is minimal, indicated by areas of small, scattered flakes, where the surface appears rough and inhomogeneous, with many defect areas signifying a high degree of carbon atom irregularity. This indicates that the 5 VA input energy was insufficient to provide the activation energy needed to recrystallize the carbon into an optimal nanocrystalline form. At an FJH voltage of 10 VA, the BLAC morphology shows a much better nano-regular crystal structure. Flake areas are clearer and broader, indicating the growth of ordered graphitic domains, with a smoother surface and increased crystal definition. Pores appear hierarchical, consisting of a combination of micro and mesopores, with larger pore size and balanced distribution. Defect areas around the flakes are fewer and controlled, showing a robust and conductive carbon structure. Meanwhile, BLAC from FJH at 15 VA shows a structure with crystal disturbance. Although larger flakes are present, defect areas increase significantly again, where over-energy heating can cause carbon crystal degradation reactions, leading to irregularities and overly large macropores that reduce the effectiveness of the active area. Pores in this sample are dominant at the meso to macro level with irregular dimensions. Across the entire surface, micropores with sizes around 2 μ m were identified, becoming important sites for ionic diffusion when the material is used as an electrode.

EDX analysis results on FJH-processed BLAC show changes in elemental composition with increasing input voltage. Based on Figure 4., at voltages of 5 VA and 10 VA, the dominance of carbon (CK, ~60 wt%) and oxygen (OK, ~19%) especially C K α (~0.28 keV), O K α (~0.52 keV), Si K α (~1.74 keV), and Ca K α (~3.69 keV), which originate from electron transitions from the L-shell to the K-shell following inner-shell ionization. This indicates a carbon structure rich in oxygen functional groups, supported by the presence of natural leaf minerals like Si, Ca, and Cl. Increasing the voltage to 15 VA caused an increase in carbon content to 72.47 wt% and a significant decrease in oxygen (16.18%) which is reflected by the increased intensity of the C K α peak and reduced O K α peak,

Figure 3.
The morphology of
the BLAC consists of
SEM images:
(a) voltage 5 VA;
(b) voltage 10 VA, (c)
voltage 15 VA;
(d) the visual of
coated and
(e) uncoated
electrodes

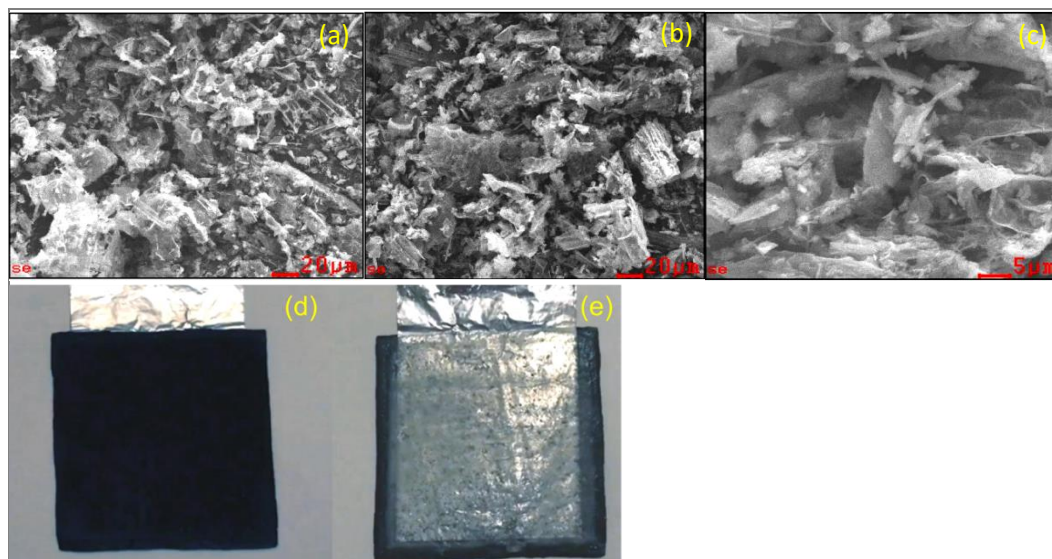
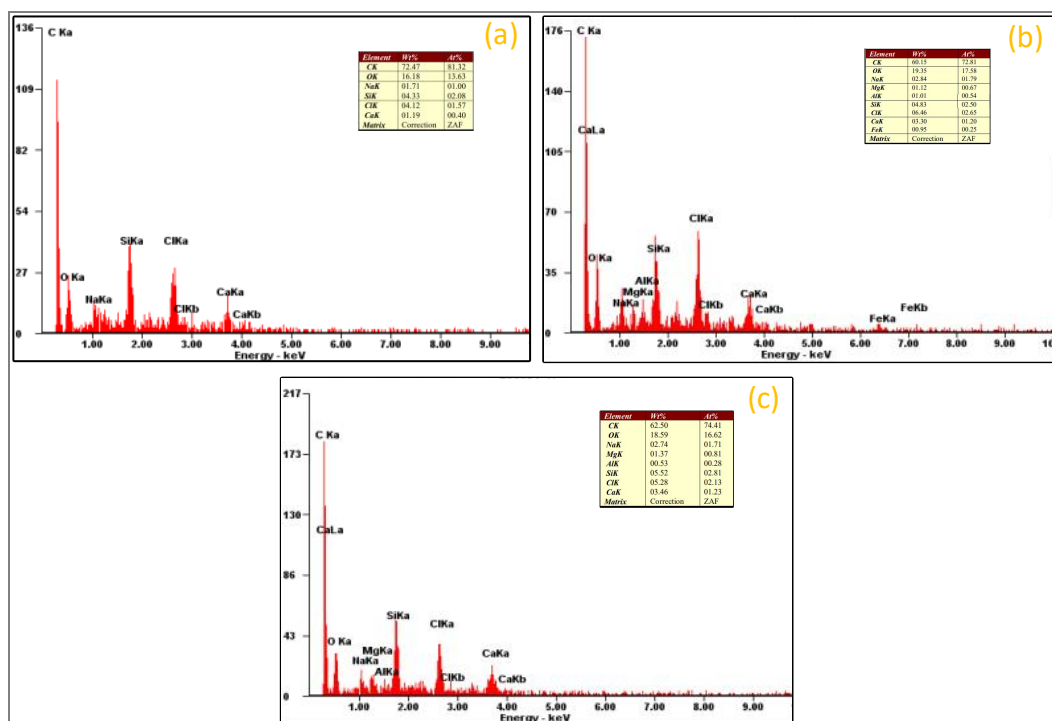


Figure 4.
EDX result of BLAC
based on FJH input
current variation:
(a) 5 VA;
(b) 10 VA;
(c) 15 VA



indicating enhanced carbon ordering and reduced oxygen functional groups due to higher FJH input energy. This also indicates enhanced carbon purity and a more ordered carbon structure due to improved graphitization at higher FJH energy input, rather than solely thermal decomposition. The presence of mineral residues such as SiK and CaK (~4% each) in all samples is suspected to originate from KOH activation and leaf ash [46], [47]. This pattern is consistent with previous studies reporting that increasing voltage in FJH tends to reduce non-carbon elements while increasing the degree of graphitization [40]. Furthermore, the relatively high oxygen content suggests the presence of oxygen-containing functional groups such as hydroxyl (–OH), carbonyl (C=O), and carboxyl (–COOH), which are known to contribute to pseudocapacitive behavior in supercapacitor electrodes.

XRD testing was conducted to determine the surface structure of BLAC. However, the number of X-ray reflections at each contact angle can provide different interpretations of the results. EDX detects elemental composition regardless of crystallinity, whereas XRD only identifies crystalline phases; therefore, minor or amorphous elements observed in EDX may not produce detectable diffraction peaks in XRD [48]. Broader XRD peaks indicate more X-rays are reflected to the detector at various contact angles. As shown in Figure 5, the presence of larger BLAC materials like graphite flakes will produce broader peaks as explained by research [30], [49].

XRD analysis of BLAC shows two broad main diffraction peaks, at around $2\theta = 23^\circ$ and 43° , indicating the presence of an amorphous structure with slight graphite content [50]. The broad peak at 23° is related to the (002) plane of turbostratic graphite structure, while the peak around 43° is associated with the (100) plane. The highest intensity was observed in the 5 VA FJH BLAC sample (red line), indicating a higher degree of crystallinity compared to the other two samples. Meanwhile, the 10 VA FJH (blue line) and 15 VA FJH (green line) samples showed broader and more diffuse peaks, signifying a higher amorphous level due to increased disorder and structural defects during the heating process. This indicates that increasing the voltage in the FJH process increases the degree of disorder and reduces crystallite size, resulting in activated carbon with a more amorphous structure, which is generally beneficial for applications like supercapacitors [51]. Further analysis of the SEM images was performed by generating surface visualizations of the BLAC samples using ImageJ software. This visualization was obtained from 8-bit images, mapped based on pixel brightness levels in the form of byte values, ranging from 0 to 255, with higher values indicating brighter areas. To clarify the interpretation of pore locations, defects, and carbon flakes, a *lookup table* coloring scheme based on ImageJ's built-in fire palette was used, where the highest byte value is displayed in yellow and the lowest in blue [49]. The graphical representation of the surface is shown in Figure 6. The relationship between XRD data and SEM images was analyzed by matching the characteristics of the XRD peaks to the surface patterns from the SEM images. It was found that areas with low brightness levels on the surface image tend to be associated with broader XRD peaks.

Subsequently, the BLAC specimens underwent FTIR testing using a Shimadzu instrument with 4 cm^{-1} resolution and Happ-Genzel apodization as shown in Figure 7. The analysis results showed

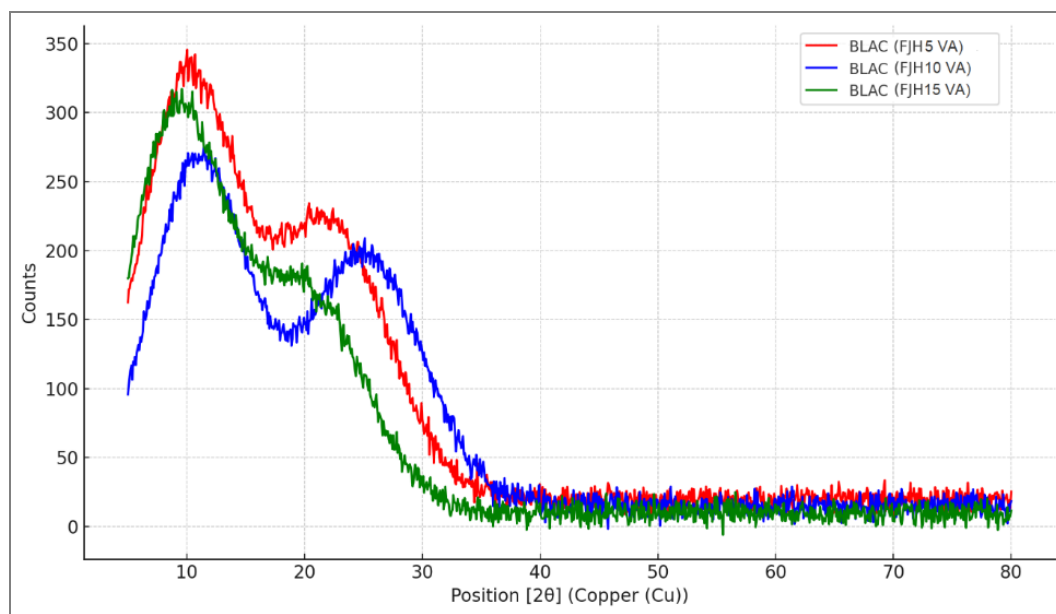


Figure 5.
XRD results of BLAC:
5 VA (red line), 10 VA
(blue line), and 15 VA
(green line)

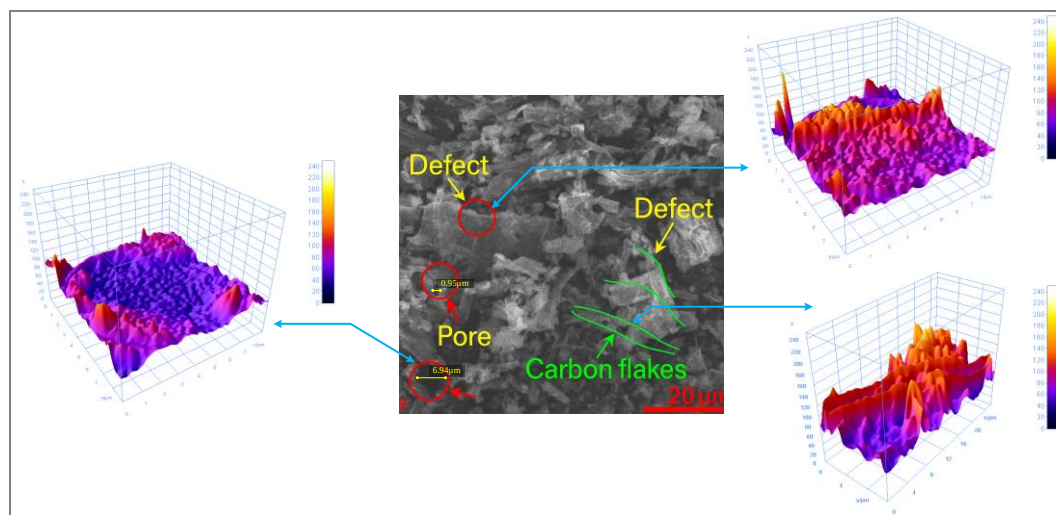


Figure 6.
SEM image analysis
result of BLAC from
ImageJ

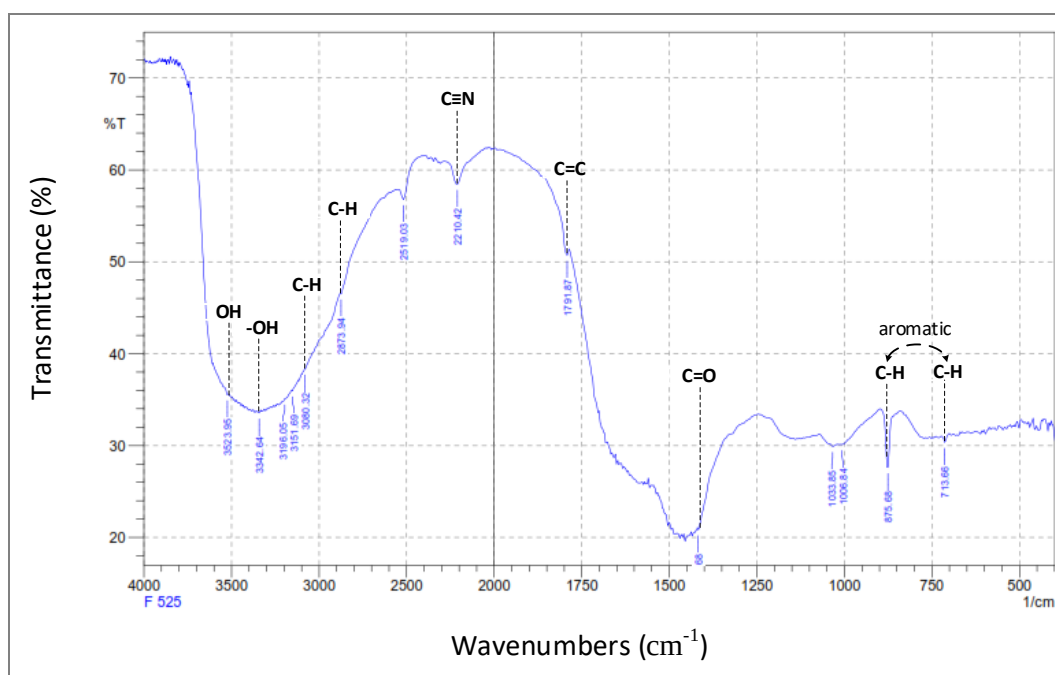


Figure 7.
FTIR result of BLAC

several significant peaks indicating functional groups on the BLAC surface. The FTIR spectrum provides information on the types of bonds and functional compounds such as hydroxyl (-OH), carbonyl (C=O), carboxylate (-COO^-), and aromatic groups, which play important roles in the chemical properties and surface reactivity of activated carbon.

Peaks at 713.66 cm^{-1} and 875.68 cm^{-1} indicate C-H stretching vibrations in aromatic compounds and carboxyl group (O-H) deformation, commonly found in activated carbon materials. Strong peaks at 1417.68 cm^{-1} and 1791.87 cm^{-1} indicate the presence of C=O (carbonyl) and C=C (aliphatic/aromatic) bonds, while a broad peak at 3342.64 cm^{-1} indicates hydroxyl (-OH) groups from phenolic compounds or adsorbed water. These peaks prove that BLAC has oxygen-rich active sites, which are beneficial for energy storage applications. The varying peak intensity distribution, such as high peaks at 2210.42 cm^{-1} ($\text{C}\equiv\text{N}$ bond or N-H vibration) and 2873.94 cm^{-1} (aliphatic C-H stretching), shows the complexity of the BLAC chemical structure derived from the lignocellulosic content of banana leaf. The presence of small peaks at 3080.32 cm^{-1} (aromatic C-H vibration) and 3523.95 cm^{-1} (free O-H bond) strengthens the suspicion that KOH activation successfully opened pores while retaining polar functional groups. This pattern is consistent with the high surface area ($>1000\text{ m}^2/\text{g}$) reported in previous studies, where oxygen groups enhance the hydrophilicity and energy storage capacity of GO [52]. This FTIR data is also supported by SEM-EDX results showing a homogeneous distribution of carbon and oxygen elements (see Figure 3.).

3.3. Discussion

Variations in FJH voltage resulted in differences in the crystallinity structure of the BLAC material. Morphological analysis via SEM to observe surface structure and pore distribution and EDX to understand elemental composition and distribution, phase analysis using XRD, and elemental analysis with FTIR have revealed the factors causing differences in electrical conductivity and specific capacitance in BLAC electrodes. Increasing the FJH input voltage does not directly result in an ideal uniformity of the BLAC crystal structure for supercapacitor electrode applications. This indication is shown by the use of 10 VA FJH voltage yielding higher specific capacitance yet with lower resistance. At this condition, the formation of a hierarchical micro-mesoporous structure enhances ion transport and charge storage, while sufficient graphitic ordering improves electron conductivity. In addition, the presence of oxygen-containing functional groups contributes to pseudocapacitive behavior, further increasing capacitance. Similar trends have been reported in biomass-derived carbon materials, where an optimal activation energy leads to improved electrochemical performance, whereas insufficient or excessive energy input results in poor conductivity or loss of active surface area, respectively [53].

SEM images revealed that BLAC under optimal conditions is shown in the 10 VA variation sample, which has a balanced hierarchical pore distribution between micro and mesopores. Conversely, at the high voltage of 15 VA, it triggered excessive formation of macropores which

actually reduced the effective surface area. Carbon porosity in the electrode functions as an electron storage reservoir and an efficient ion transport pathway [47]. Micropores provide high surface area for electric double-layer formation, while mesopores facilitate ion diffusion towards active surfaces [54]. This combination enhances specific capacitance and accelerates the charge-discharge process. Meanwhile, if the pore structure is too large, as seen at 15 VA, the number of effective areas decreases, thus reducing charge storage capacity, although conductivity may remain high due to better carbon purity.

Phase analysis using XRD in Figure 5. shows that FJH voltage variation reveals a significant evolution in the crystalline morphology of the BLAC material. Lower voltage (5 VA) produced an amorphous surface with sub-nano sized crystallites, as indicated by the broadening of the diffraction peak at $2\theta \approx 24^\circ$. This is triggered by insufficient activation energy for the formation of graphitic structures in BLAC. Conversely, the optimal condition is shown in the 10 VA FJH voltage variation, which shows a sharper peak, indicating the formation of nanoflake graphitic domains sized 2-5 nm with better structural regularity. A more regular GO surface structure can trigger freer electron movement, enhancing electrode conductivity, which plays a direct role in the efficiency of charging and discharging in supercapacitors [55]. As shown in Figure 2., the 10 VA FJH voltage variation BLAC has maximized surface area and ion kinetics, while high structural regularity maximizes electron conductivity and long-term stability. This synergy ultimately results in a supercapacitor with not only high initial capacitance but, more importantly, exceptional capacitance retention after many cycles, which is a critical parameter for large-scale commercial applications.

The surface chemical composition of BLAC also influences electrode performance through the presence of oxygen functional groups. FTIR confirms the specific functional groups (e.g., hydroxyl, carbonyl, carboxyl), while EDX identifies the elemental composition. A high elemental abundance of carbon and oxygen, as detected by EDX, strongly suggests the presence of organic functional groups, which is then supported and specified by the functional group information obtained from the FTIR results. Oxygen groups on BLAC can act as pseudocapacitance active centers, contributing to increased storage capacity through mild redox charge transfer mechanisms. Oxygen groups play a role in local interactions with electrons and electrolyte ions, facilitating kinetically favorable charge storage without damaging the conductive graphene network [56]. As shown through the performance test of the 10 VA variation sample, which shows an optimal balance between oxygen groups as pseudocapacity sites and the conductive graphitic structure, enhancing coulomb efficiency and cycle stability (see Figure 5.). This condition indicates that electrons can travel through the material with minimal resistance. Low resistance contributes to reduced energy loss as heat, maintaining the overall energy efficiency of the supercapacitor system. Conversely, the material at 5 VA has an amorphous structure that hinders electron pathways, increasing resistance and decreasing capacitance, while at 15 VA, although it has fairly low resistance, the macro pore structure and defects in nanocrystals reduce the effective active area.

Cycle stability reaching over 95% after 500 cycles for 10 VA BLAC indicates the electrode's resistance to structural and chemical degradation during repeated performance testing. In the 10 VA variation sample, there is stability of strong sp² bonds and a non-aggressive distribution of oxygen groups, so the carbon material maintains its structure and electronic properties without the significant formation of trapping centers. This is important to ensure capacitor performance does not drastically decline due to detrimental physical or chemical changes.

The aspects of morphology, crystal structure, and surface chemistry that govern electron and ion transport pathways have direct implications for supercapacitor performance. Conductivity is highly influenced by the level of defects and functional groups that induce electron scattering, as seen in Figure 6. BLAC with controlled defects and sufficient pores will optimize the electron hopping and tunneling processes essential in supercapacitor energy storage. The utilization of banana leaf waste biomass to produce graphene oxide electrodes via FJH has revealed findings on the use of renewable materials in energy applications. FJH electrothermal activation with high temperature and short time has triggered carbon atom reorientation and controlled defects in BLAC, thereby improving electron pathways and more optimal energy storage capability.

Another important factor that affects electrochemical performance of supercapacitor electrodes is mass loading. Mass loading directly affects ion diffusion pathways, internal resistance, and effective utilization of active material [57]. A relatively high mass loading (~20 g per electrode) ensure structural integrity and full surface coverage of the current collector. Mass loading significantly influences electrochemical performance, where higher loading increases areal capacitance but can reduce specific capacitance and rate capability due to limited ion diffusion and

increased internal resistance [58]. However, high mass loading can introduce limitations in ion diffusion and increase internal resistance due to longer transport pathways within the electrode material. This may lead to partial utilization of active material, particularly at higher current densities. Conversely, higher mass loading can also increase the total stored charge due to the larger amount of active material available. Therefore, the observed electrochemical performance represents a balance between these competing effects. The optimal performance observed at 10 VA suggests that the pore structure and conductivity of the material effectively mitigate diffusion limitations even at relatively high mass loading.

The electrochemical performance of the BLAC electrode with previously reported materials were compared in Table 1. The developed electrode exhibits a specific capacitance of 345 F g^{-1} , which is comparable to biomass-derived carbon, metal oxide composites, and MXene-based electrodes. Although some materials show similar or higher values, they often involve more complex synthesis or non-renewable precursors. In contrast, this study offers a sustainable and efficient approach using banana leaf waste and the ultrafast FJH method, demonstrating competitive performance with simplified processing.

The electrochemical performance of BLAC electrodes can be explained through a combined charge storage mechanism involving electric double-layer capacitance (EDLC) and pseudocapacitance [59]. The porous carbon structure provides a large surface area that facilitates electrostatic ion adsorption at the electrode-electrolyte interface, contributing to EDLC behavior [60]. In addition, oxygen-containing functional groups identified by FTIR analysis, such as hydroxyl and carbonyl groups, contribute to faradaic redox reactions, enhancing pseudocapacitive charge storage [61]. The hierarchical pore structure, consisting of micro- and mesopores, supports efficient ion transport and electrolyte accessibility, thereby improving rate capability and capacitance retention [62]. The superior performance observed at 10 VA is attributed to the optimal balance between graphitic conductivity, controlled defect density, and functional group distribution, which together facilitate both electron transport and ion diffusion [63]. Furthermore, cycling stability results demonstrate that the electrode retains 95% of its capacitance after 500 cycles, indicating good structural integrity and electrochemical durability [64]. Although repeatability tests were not systematically performed, the consistent electrochemical trends across different voltage conditions suggest reliable material behavior. Future work will focus on systematic repeatability analysis and extended cycling tests to further validate long-term performance.

Table 1.
Comparison of
electrochemical
performance with related
studies

Material / Electrode	Synthesis Method	Specific Capacitance (F g^{-1})	Key Feature	Ref.
Banana leaf-derived GO (this work)	Flash Joule Heating (FJH) + KOH activation	345	Sustainable biomass, ultrafast synthesis	This work
Biowaste-derived activated carbon	Chemical activation	~250–320	Renewable precursor, porous structure	[65]
NiCo_2O_4 / MnFe_2O_4 composite	Hydrothermal / solid-state	~300–400	High pseudocapacitance	[66]
NiO nanoparticles	Chemical synthesis	~200–350	Battery-type behavior	[67]
MXene-based electrode	Etching + assembly	~300–450	High conductivity, layered structure	[68]
N-doped graphene oxide composite	Chemical modification	~280–360	Enhanced conductivity + defects	[69]

4. Conclusion

This study demonstrates that porous graphene oxide derived from banana leaf waste via Flash Joule Heating (FJH) can function as an effective supercapacitor electrode material. Among the tested conditions, the 10 VA input voltage produced the optimal structure, characterized by a balanced micro–mesoporous network, resulting in the highest specific capacitance (345 F g^{-1}), lowest resistance (0.65Ω), and excellent cycling stability (95% retention after 500 cycles). Lower voltage (5 VA) resulted in insufficient graphitization and higher resistance, whereas higher voltage (15 VA) led to excessive macropore formation, reducing effective surface area and capacitance. These findings confirm that precise control of FJH parameters is essential to achieve optimal electrochemical performance. Furthermore, this work highlights the potential of banana leaf biomass as a low-cost, sustainable precursor for advanced energy storage materials.

Nomenclature

BLAC	: Banana Leaf Activated Carbon	sp ²	: Type of carbon hybridization
FJH	: Flash Joule Heating	KOH	: Potassium hydroxide (activating agent)
GO	: Graphene Oxide	SEM	: Scanning Electron Microscopy
SC	: Supercapacitor	EDX	: Energy Dispersive X-ray spectroscopy
EDLC	: Electric Double-Layer Capacitance	XRD	: X-ray Diffraction
VA	: Applied voltage in the FJH process (Volt-Ampere)	FTIR	: Fourier Transform Infrared Spectroscopy
F g ⁻¹	: Specific capacitance (Farad per gram)	2θ	: Diffraction angle in XRD analysis
Ω	: Electrical resistance (Ohm)		

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Authors' Declaration

Authors' contributions and responsibilities – The authors made substantial contributions to the study's conception and design. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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