Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 8, No.4, October 2026, pp. 02604025-01 ~ 02604025-012
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v8i4.3992

Banana Peel-Derived Activated Carbon/MnO_2 Composites for Supercapacitor Electrode Applications

Katarina Herwanti[1*], Saptono Nugrohadi[2], Muchamad Taufiq Anwar[3], Stanislaus Christo Petra Nugraha[4], Dail Umamil Asri[5], Noening Andrijati[6]

[1]Faculty of Education and Psychology, Universitas Negeri Semarang, Jl. Raya Banaran, Sekaran, Gunung Pati, Semarang City, Central Java 50229, Indonesia

[2]SMA Negeri 3 Salatiga, Jl. Kartini No.34, Salatiga 50711, Central Java, Indonesia

[3]Auotomotive Industry, Information System, Politeknik STMI Jakarta, Jl. Letjen Suprapto No.26, Central Jakarta,10510, Jakarta, Indonesia

[4]School of Humanities, Social Sciences, and Law, University of Dundee, Nethergate, Dundee, Scotland, UK, DD1 4HN

[5]Faculty of Cultural Sciences, Diponegoro University, Jl.Dr. Antonius Suroyo, Tembalang, Semarang City 50275, Central Java, Indonesia

[6]Faculty of Education and Psychology, Universitas Negeri Semarang, Jl. Raya Banaran, Sekaran, Gunung Pati, Semarang City, Central Java 50229, Indonesia

*katarinaherwanti@mail.unnes.ac.id

Abstract. Banana peel waste is an abundant agricultural by-product with high carbon content but remains largely underutilized. This study presents a preliminary investigation into the conversion of banana peel waste into activated carbon and its integration with manganese dioxide (MnO_2) to produce biomass-derived composite electrodes for supercapacitor applications. Activated carbon was prepared by carbonization followed by chemical activation using 30 wt% H_3PO_4, while MnO_2–carbon composites were synthesized hydrothermally at 120 °C for 4 h using different carbon-to-MnO_2 mass ratios. The composites were characterized by Brunauer–Emmett–Teller (BET) analysis, and their electrochemical performance was evaluated by cyclic voltammetry (CV) in a three-electrode system with 6 M KOH electrolyte. Repeated measurements were conducted to improve data reliability. Among the investigated samples, MnO_2–BAC–1 exhibited the highest average specific capacitance of 108.87 F g^{-1} at a scan rate of 0.05 V s^{-1}, which corresponded to the largest pore volume. Although the present findings are limited to BET and CV analyses, they demonstrate the feasibility of utilizing banana peel waste as a sustainable precursor for MnO_2–carbon composite electrodes and provide a basis for further structural characterization and comprehensive electrochemical evaluation.

Keywords: activated carbon, banana peel waste, biomass valorization, MnO_2–carbon composite, cyclic voltammetry, supercapacitor electrode, three-electrode system.

(Received 2025-06-11, Revised 2026-08-11, Accepted 2026-08-03, Available Online by 2026-09-08)

1. Introduction

Banana (Musa spp.) is one of the most extensively cultivated tropical crops in Indonesia, generating a substantial amount of agricultural residue in the form of banana peel waste. In practice, these residues are commonly discarded, left to decompose naturally, or openly burned, resulting in localized waste accumulation, unpleasant odors, and avoidable environmental pollution. Nevertheless, banana peels contain abundant lignocellulosic components, including cellulose, hemicellulose, and lignin, which provide a renewable carbon source for the production of porous carbon materials suitable for electrochemical applications [1]. Converting banana peel waste into functional carbon materials therefore represents an attractive strategy for biomass valorization while simultaneously addressing environmental concerns associated with agricultural waste disposal [2-3].

Biomass-derived activated carbon has received considerable attention as an electrode material for supercapacitors because of its well-developed pore structure, large specific surface area, chemical stability, and relatively low production cost [4], [5], [8], [10]. Numerous agricultural wastes, including coconut shells, rice husks, bamboo, coffee grounds, and fruit peels, have been successfully converted into porous carbon electrodes with promising electrochemical properties [6], [11], [13]. Among these biomass resources, banana peel is particularly attractive owing to its widespread availability, high carbon content, and ability to develop hierarchical porous structures after chemical activation and thermal treatment. However, activated carbon derived solely from banana peel generally functions as an electric double-layer capacitor (EDLC) material, resulting in moderate specific capacitance because charge storage is dominated by electrostatic ion adsorption rather than Faradaic reactions [14-15].

To overcome this limitation, the incorporation of pseudocapacitive materials into porous carbon matrices has become a widely adopted strategy for enhancing charge-storage performance. Among various transition-metal oxides, manganese dioxide (MnO_2) has emerged as one of the most promising candidates because of its high theoretical specific capacitance (1,370 F g^{-1}), environmental friendliness, natural abundance, and relatively low cost [16], [24], [25]. Nevertheless, the intrinsically low electrical conductivity and limited ion transport characteristics of MnO_2 often restrict its practical electrochemical performance when used as a single-component electrode. Hybridization with conductive porous carbon has therefore been extensively explored to combine electric double-layer capacitance from carbon with the Faradaic pseudocapacitance of MnO_2, thereby improving electron transport, electrolyte accessibility, and overall electrochemical performance [16], [17- 20].

Recent studies have demonstrated encouraging electrochemical performance for MnO_2–carbon composites prepared from various biomass precursors, including rice husks, bamboo, pomelo peel, orange peel, palm fibers, and mixed agricultural residues [21-23] Reported specific capacitance values generally range from approximately 80 to more than 250 F g^{-1} depending on precursor composition, activation method, pore architecture, electrolyte, and testing conditions. These variations indicate that direct comparison among published studies remains challenging because electrochemical performance is strongly influenced by synthesis parameters and measurement protocols. Furthermore, only a limited number of investigations have specifically examined MnO_2-modified activated carbon derived from banana peel using hydrothermal synthesis while systematically evaluating the influence of MnO_2 loading on pore characteristics and electrochemical behavior under identical experimental conditions in a 6 M KOH electrolyte using cyclic voltammetry at a scan rate of 0.05 V s^{-1}.

Based on the research gap identified above, this study investigates the utilization of banana peel waste as a precursor for activated carbon and its subsequent integration with MnO_2 through a hydrothermal synthesis route to develop composite electrode materials for supercapacitor applications [9], [12]. The

novelty of this work lies in systematically evaluating the influence of different activated carbon-to-MnO_2 mass ratios on pore characteristics and electrochemical performance while maintaining an identical synthesis protocol and testing configuration. Unlike previous studies that primarily focused on either biomass-derived activated carbon or MnO_2-based electrodes independently, this study examines the synergistic effect of combining both materials under controlled hydrothermal conditions using a 6 M KOH electrolyte and cyclic voltammetry measurements in a three-electrode system. Specifically, this study aims to produce activated carbon from banana peel waste, synthesize MnO_2–carbon composites with different mass ratios, characterize their specific surface area and pore properties using Brunauer–Emmett–Teller (BET) analysis, and evaluate their preliminary electrochemical performance using cyclic voltammetry (CV). Although the present work is limited to a preliminary electrochemical assessment, the findings are expected to provide fundamental insights into the development of sustainable biomass-derived composite electrodes and to establish a scientific basis for future investigations involving advanced structural characterization and comprehensive electrochemical validation.

2. Methods

2.1 Type and Research Design

This study adopted a laboratory-based quantitative experimental design to investigate the feasibility of producing MnO_2–carbon composites from banana peel-derived activated carbon for supercapacitor electrode applications. The experimental work comprised four sequential stages: preparation of the biomass precursor, production of activated carbon, hydrothermal synthesis of MnO_2–carbon composites with different MnO_2 loadings, and physicochemical and electrochemical characterization. Rather than providing comprehensive device validation, this work was designed as a preliminary proof-of-concept study to examine how variations in MnO_2 loading influence the textural properties and cyclic voltammetry (CV)-based electrochemical performance of the resulting composites. Primary data were obtained directly from laboratory experiments, whereas secondary information was collected from peer-reviewed publications relevant to biomass-derived carbon materials and electrochemical energy storage.

2.2 Research Materials

Banana peels with an initial moisture content of approximately 80% were used as the biomass precursor for activated carbon production. All reagents, including MnO_2 (99% purity, Sigma-Aldrich), H_3PO_4 (30%, Merck), NaOH (1 M, Merck), Nafion (5 wt%, Sigma-Aldrich), isopropanol (99.5%, Merck), and KOH (6 M, Merck) were of analytical grade and used without further purification. Distilled water was used throughout the washing and solution preparation processes.

2.3 Research Instruments

The main instruments used in this study included an electric tube furnace for carbonization and thermal activation, a Teflon-lined stainless steel autoclave for hydrothermal synthesis, a drying oven, an ultrasonic cleaner, a Brunauer–Emmett–Teller (BET) analyzer for surface area and pore structure analysis, and a μStat 400 bipotentiostat/galvanostat for electrochemical measurements in a three-electrode system. Prior to surface area analysis, instrument calibration was performed according to the manufacturer's standard procedures.

2.4 Experimental Procedures

2.4.1 Preparation of Activated Carbon from Banana Peel

Fresh banana peels were washed thoroughly with distilled water to remove adhering dirt and impurities, then cut into small pieces of approximately 3 cm. The cleaned peels were oven-dried at 60 °C for 24 h to reduce moisture content before carbonization. The dried precursor was then carbonized in a tube furnace at 550 °C for 2.5 h under an inert nitrogen atmosphere with a heating rate of 5 °C min^{-1}.

Figure 1. Washing process of carbon using ultrasonic cleaner
(Source: Authors' documentation)

After carbonization, the resulting carbon material was ground and sieved through a 100-mesh sieve to obtain a more uniform particle size. The sieved carbon was washed with distilled water using an ultrasonic cleaner and then dried at 100 °C for 12 h. The carbonization process yielded approximately 35% char from the dried precursor.

Figure 2. Chemical activation process through impregnation
(Source: Authors' documentation)

The carbonized banana peel was chemically activated through impregnation in a 30 wt.% H_3PO_4 solution for 24 h. To ensure reproducibility across experimental batches, the mixture was prepared using a strictly controlled carbon-to-activating-agent mass ratio of 1:4. Following the impregnation process, the material was washed with 1 M NaOH to neutralize residual acid and subsequently rinsed several times with distilled water until the filtrate reached a neutral pH. The resulting activated carbon was dried and further subjected to thermal activation at 500 °C for 1 h to promote pore formation and improve its textural properties.

2.4.2 Hydrothermal Synthesis of MnO_2–Carbon Composites

The activated carbon (BAC) was combined with commercial MnO_2 powder at mass ratios of 5:0.5, 5:1, and 5:1.5. Each mixture was dispersed in distilled water and stirred until a homogeneous suspension was obtained before being transferred into a sealed autoclave. Hydrothermal treatment was performed at 120 °C for 4 h. After the reaction, the precipitated product was filtered, washed several times with distilled water and alcohol, dried at 100 °C for 12 h, and then heat-treated at 400 °C for 1 h to obtain the final composite powders. The resulting materials were coded as MnO_2–BAC–0.5, MnO_2–BAC–1, and MnO_2–BAC–1.5, corresponding to the mass of MnO_2 relative to 5 g of activated carbon.

The obtained composite powders were designated as MnO_2–BAC–0.5, MnO_2–BAC–1, and MnO_2–BAC–1.5, representing increasing MnO_2 loading while maintaining a constant activated carbon mass of 5 g.

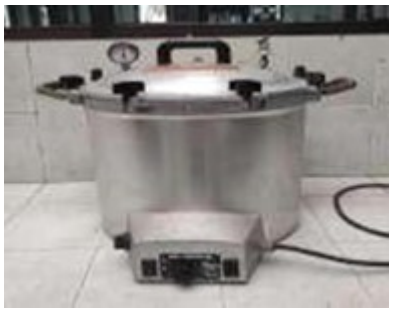

Figure 3. Hydrothermal synthesis of MnO_2–Carbon using autoclave
(Source: Authors' documentation)

Figure 4. MnO_2–Carbon composites obtained from hydrothermal synthesis
(Source: Authors' documentation

2.5. Material Characterization

The textural properties of the synthesized composites were analyzed using Brunauer–Emmett–Teller (BET) analysis to determine specific surface area, average pore diameter, and total pore volume. Prior to the measurement, the samples were degassed at 150 °C for 6 h under vacuum conditions to remove adsorbed moisture and surface contaminants.

Figure 5. BET analyzer
(Source: Authors' documentation)

Figure 6. Three-electrode system for electrochemical testing
(Source: Authors' documentation)

Electrochemical performance was evaluated by Cyclic Voltammetry using a three-electrode system with 6 M KOH as the electrolyte. The working electrode slurry was prepared by mixing 10 mg of active material, 1 mL of isopropanol, and 20 μL of nafion. The suspension was sonicated until homogeneous and then drop-cast onto the electrode surface.

The present characterization was intentionally limited to BET analysis for evaluating textural properties and cyclic voltammetry for preliminary electrochemical assessment. Consequently, structural features such as crystal phase, surface morphology, elemental distribution, and surface functional groups were not directly examined in this study. Any discussion concerning the role of MnO_2 distribution or structural interaction is therefore presented as a reasonable interpretation based on BET and CV results rather than as direct experimental confirmation.

2.5.1 Calculation of Specific Capacitance

The specific capacitance was calculated from the *cyclic voltammetry* response using the integrated area of the CV curve over the selected potential window. Prior to integration, the current baseline was corrected to minimize the contribution of non faradaic background and instrumental drift. The capacitance value was determined from the stabilized CV cycle used for final analysis, namely the last cycle recorded under each testing condition. The calculated capacitance values therefore represent apparent specific capacitance derived from cyclic voltammetry measurements under the specified experimental conditions. The specific capacitance, C (*F/g*), was calculated using the following equation:

$$C = \frac{A}{2 \times m \times S \times \Delta V} \quad (1)$$

where A is the integrated area of the CV curve ($V \cdot A$), m is the mass of the active electrode material (g), S is the scan rate (V/s), and ΔV is the potential window (V). The active mass deposited on each electrode was measured using an analytical balance and recorded to an appropriate precision, because uncertainty in low mass loading can strongly influence the calculated capacitance.

2.6. Replication and Statistical Analysis

All electrochemical and physical characterization data were analyzed quantitatively and comparatively among the three composite variations. For each composite sample, electrochemical measurements consisted of three consecutive Cyclic Voltammetry (CV) cycles performed on the same prepared electrode to assess measurement consistency. The reported specific capacitance represents the mean value calculated from these three consecutive CV cycles. These repeated cycles represent technical repeated measurements rather than independent experimental replicates. Owing to the exploratory nature of the study and the absence of independent replicate electrodes, no inferential statistical analysis was performed. Accordingly, differences among the composite samples were interpreted descriptively as observed experimental trends and should not be considered statistically significant differences.

2.7. Safety and Environmental Considerations

The synthesis and activation procedures involved corrosive chemicals, particularly phosphoric acid and sodium hydroxide. Therefore, all experimental work was conducted using appropriate laboratory protective equipment, including gloves, a lab coat, and safety glasses. Washing, neutralization, and rinsing steps were carried out carefully to reduce the risk of chemical exposure and prevent uncontrolled acidic or alkaline discharge. Liquid waste generated during the activation and washing processes was neutralized prior to disposal in accordance with standard laboratory safety and waste management procedures.

2.8. Study Limitations

This study focused on preliminary evaluation using BET and CV analyses. Advanced structural characterization (XRD, SEM/EDX, Raman or FTIR) and complementary electrochemical analyses (GCD, EIS and cycling stability) were beyond the scope of the present investigation. Consequently, mechanistic interpretations regarding MnO_2 distribution, charge-transfer behavior and long-term electrochemical stability remain preliminary and should be verified in future studies.

3. Results and Discussion

3.1. Morphological and Physical Characteristics of MnO_2–Carbon Composites

The synthesized MnO_2–carbon composites derived from banana peel-based activated carbon were obtained as fine powders with a dark gray to black appearance. The products exhibited a relatively friable texture, were insoluble in water, and gradually settled after dispersion, indicating the formation of particulate composite materials rather than colloidal suspensions. These macroscopic characteristics are generally consistent with biomass-derived carbon composites reported in previous studies, where activated carbon serves as the supporting matrix for electrochemically active transition-metal oxides [10], [25]. It should be emphasized that the present observations are limited to the macroscopic appearance of the synthesized materials. Since no microscopic or crystallographic characterization (e.g., SEM, TEM, or XRD) was performed, the morphology, particle distribution, crystallinity, and interaction between MnO_2 and the carbon matrix cannot be directly verified. Consequently, any discussion regarding the structural role of MnO_2 in the composite should be regarded as an interpretation based on

the available BET and electrochemical results rather than direct experimental confirmation. Accordingly, this study should be considered a preliminary assessment of biomass-derived MnO_2–carbon composites prior to comprehensive structural characterization.

3.2. BET Surface Area and Pore Structure Analysis

The *Brunauer–Emmett–Teller* analysis was used to evaluate the textural properties of the synthesized composites, including specific surface area, average pore diameter, and total pore volume. As shown in Table 1, the MnO_2–BAC–0.5 sample exhibited the highest specific surface area of 434.15 m^2/g, followed by MnO_2–BAC–1 with 389.86 m^2/g and MnO_2–BAC–1.5 with 376.33 m^2/g. In contrast, the total pore volume reached its highest value in MnO_2–BAC–1 at 0.09 cc/g, while MnO_2–BAC–0.5 and MnO_2–BAC–1.5 exhibited 0.08 and 0.07 cc/g, respectively. The results are summarized in Table 1.

Table 1. Pore characteristics of MnO_2–carbon composites obtained from BET analysis

Material	Surface Area (m^2/g)	Average Pore Diameter (nm)	Total Pore Volume (cc/g)
MnO_2-BAC-0,5	434,15	2,02	0,08
MnO_2-BAC-1	389,86	2,01	0,09
MnO_2-BAC-1,5	376,33	2,01	0,07

Source: Authors' experimental data (2026)

These results indicate that increasing the amount of MnO_2 does not produce a proportional improvement in the textural characteristics of the composite. Instead, the intermediate composition (MnO_2–BAC–1) appears to provide a more balanced pore architecture, combining a relatively high pore volume with only a moderate reduction in specific surface area. Because electrolyte ions require sufficient pore accessibility during charge storage, pore volume may play a more influential role than surface area alone under the electrochemical conditions employed in this study.

The average pore diameter remained nearly constant (2.01–2.02 nm) for all samples, suggesting that the synthesis conditions did not substantially modify the dominant pore size. Based solely on BET measurements, the composites can therefore be considered to possess relatively similar pore dimensions, while differences among the samples mainly arise from variations in accessible surface area and pore volume. These characteristics are generally regarded as favorable for supercapacitor electrodes because they facilitate electrolyte penetration while preserving a sufficiently large electrochemically accessible interface [5], [15].

A gradual decrease in specific surface area with increasing MnO_2 loading was observed. One possible explanation is that part of the pore network became less accessible after incorporation of MnO_2, thereby reducing the nitrogen adsorption measured during BET analysis. Similar tendencies have been reported for MnO_2–carbon composites prepared from other biomass precursors [16], [24], [25]. However, because pore-size distribution analysis, SEM observations, and XRD characterization were beyond the scope of the present work, this interpretation should be regarded as a plausible hypothesis rather than definitive evidence. Consequently, the observed relationship between MnO_2 loading and pore characteristics should be interpreted primarily on the basis of the measured BET parameters rather than inferred structural mechanisms.

Compared with previous studies employing banana peel-derived activated carbon as a standalone electrode material, the present work introduces MnO_2 incorporation through a controlled hydrothermal route while systematically varying the MnO_2 loading under identical synthesis and electrochemical testing conditions. Although the resulting improvements should be regarded as preliminary, this experimental design provides additional insight into how MnO_2 loading influences the balance between

accessible pore structure and electrochemical performance, thereby contributing incremental knowledge to the development of biomass-derived composite electrodes for sustainable energy storage.

3.3. Electrochemical Performance through Cyclic Voltammetry

The electrochemical behavior of the synthesized composites was evaluated by *Cyclic Voltammetry* in a three-electrode configuration using 6 M KOH electrolyte. The specific capacitance values calculated at a scan rate of 0.05 V/s are summarized in Table 2. Among the tested samples, MnO_2–BAC–1 exhibited the highest average specific capacitance of 108.87 F/g, followed by MnO_2–BAC–0.5 with 101.84 F/g and MnO_2–BAC–1.5 with 82.89 F/g.

Table 2. Specific capacitance of MnO_2–carbon composites at 0.05 V/s

Material	1st Cycle (F/g)	2nd Cycle (F/g)	3rd Cycle (F/g)	Average (F/g)
MnO_2-BAC-0,5	98,12	102,15	105,26	101,84
MnO_2-BAC-1	107,89	105,40	113,33	108,87
MnO_2-BAC-1,5	78,40	81,32	88,94	82,89

Source: Authors' experimental data (2026)

The electrochemical results demonstrate that increasing the MnO_2 content does not result in a proportional increase in specific capacitance. Instead, the intermediate composition (MnO_2–BAC–1) produced the highest capacitance, suggesting that the electrochemical performance depends on achieving an appropriate balance between the porous carbon framework and the amount of electrochemically active MnO_2. Excessively low MnO_2 loading may limit the contribution of Faradaic charge storage, whereas excessive MnO_2 incorporation may reduce the accessibility of electrolyte ions to the carbon pore network. Within the limitations of the present BET and CV analyses, this interpretation is consistent with the observed variation in pore volume among the investigated composites.

A comparison between the BET and CV results further indicates that specific surface area alone cannot adequately explain the electrochemical behavior of the synthesized materials. Although MnO_2–BAC–0.5 possessed the largest BET surface area (434.15 $m^2\ g^{-1}$), it did not exhibit the highest specific capacitance. Conversely, MnO_2–BAC–1, which displayed a moderately lower surface area but the largest total pore volume (0.09 $cm^3\ g^{-1}$), achieved the best electrochemical performance. These observations suggest that pore accessibility and pore volume may contribute more substantially to ion transport during charge storage than surface area alone under the present testing conditions. Nevertheless, this relationship should be interpreted as an experimental correlation derived from BET and CV measurements rather than as direct evidence of the underlying electrochemical mechanism.

The decrease in capacitance observed for MnO_2–BAC–1.5 may indicate that further increasing the MnO_2 loading does not necessarily improve electrode performance. One possible explanation is that additional MnO_2 reduces the accessibility of the porous carbon framework, thereby limiting electrolyte penetration or electron transport. Similar trends have been reported for biomass-derived MnO_2–carbon composites prepared from other agricultural precursors, where an optimum oxide loading was required to balance pseudocapacitive contribution and ion diffusion [7], [11], [19]. However, because advanced structural characterization techniques, including XRD, SEM, and EDX, were not employed in the present study, these interpretations should be regarded as plausible hypotheses supported indirectly by the BET and CV results rather than definitive structural confirmation.

Compared with previously reported banana peel-derived activated carbon electrodes, the present work introduces a systematic evaluation of MnO_2 loading while maintaining identical synthesis conditions and electrochemical testing parameters. Although the resulting improvement should be considered incremental rather than transformative, the findings provide additional insight into the role of MnO_2 loading in balancing pore characteristics and electrochemical performance in biomass-derived composite electrodes. Consequently, this study contributes a useful preliminary dataset that may serve as a basis for future investigations employing complementary techniques such as galvanostatic charge–

discharge, electrochemical impedance spectroscopy, cycling stability, and advanced structural characterization to obtain a more comprehensive understanding of the charge-storage mechanism.

3.4. Comparative Performance with Biomass-Based Carbon Electrodes

A comparison with previously reported biomass-derived carbon electrodes indicates that the MnO_2–BAC composites developed in the present study exhibit electrochemical performance within the range reported for biomass-based supercapacitor electrodes. Under the experimental conditions employed in this work, the best-performing sample, MnO_2–BAC–1, achieved an average specific capacitance of 108.87 F g^{-1} at a scan rate of 0.05 V s^{-1} in 6 M KOH. This result suggests that incorporating MnO_2 into banana peel-derived activated carbon may enhance the electrochemical behavior compared with activated carbon alone, supporting the potential of hybrid biomass-derived electrodes for sustainable energy storage applications.

Table 3. Comparison of specific capacitance between banana peel-derived MnO_2–carbon and other biomass-based carbons

Electrode Material	Specific Capacitance (F/g)	Scan Rate (V/s)	Electrolyte	Reference
Activated carbon (banana peel)	68	0.1	1 M H_2SO_4	[26]
Carbon nanosheets (orange peel)	95	0.05	1 M Na_2SO_4	[22]
Activated carbon (bamboo)	80	0.05	6 M KOH	[18]
MnO_2–carbon (this work)	108.87	0.05	6 M KOH	Authors' data (2026)

Source: Authors' experimental data (2026)

Nevertheless, comparisons with previously published studies should be interpreted with caution because electrochemical performance is strongly influenced by numerous experimental variables, including electrode configuration, electrolyte composition, scan rate, mass loading, synthesis procedure, and capacitance calculation method. Consequently, quantitative comparisons among different studies should not be considered direct indicators of material superiority unless the testing conditions are closely matched. Within these limitations, the present findings provide additional evidence that controlled MnO_2 incorporation into banana peel-derived activated carbon represents a promising strategy for improving the electrochemical response of biomass-derived electrodes. Rather than demonstrating breakthrough performance, this study contributes incremental experimental evidence toward understanding the influence of MnO_2 loading on the relationship between pore characteristics and CV-based electrochemical behavior in banana peel-derived carbon composites.

3.5. Limitations of the Present Study

Although the BET and cyclic voltammetry (CV) results demonstrate the feasibility of producing MnO_2–carbon composites from banana peel-derived activated carbon, the present study has several limitations that should be acknowledged. First, the physicochemical characterization was limited to BET analysis; therefore, important structural information, including crystal phase, surface morphology, elemental distribution, and surface functional groups, could not be directly verified. Consequently, the interpretations presented in this work are based primarily on experimentally measured BET and CV results and should not be regarded as direct evidence of the underlying structural or electrochemical mechanisms.

Second, the electrochemical evaluation was restricted to cyclic voltammetry performed under a single testing configuration. As a result, several important performance indicators, including galvanostatic charge–discharge behavior, electrochemical impedance, rate capability, coulombic efficiency, energy

density, power density, and long-term cycling stability, remain to be investigated. Therefore, the electrochemical performance reported in this study should be interpreted as a preliminary assessment rather than a comprehensive validation of the proposed electrode material.

Despite these limitations, the present study demonstrates that incorporating MnO_2 into banana peel-derived activated carbon is associated with improved CV-based electrochemical performance compared with the activated carbon reported previously for the same biomass precursor under comparable experimental conditions. Nevertheless, broader comparisons with other biomass-derived electrode materials should be interpreted cautiously because electrochemical performance is strongly influenced by differences in synthesis procedures, electrode preparation, electrolyte composition, and testing protocols.

Future investigations should incorporate advanced structural characterization techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), Raman spectroscopy, and Fourier-transform infrared spectroscopy (FTIR), together with complementary electrochemical analyses such as galvanostatic charge–discharge (GCD), electrochemical impedance spectroscopy (EIS), and long-term cycling stability tests. These additional analyses will provide a more comprehensive understanding of the relationship between pore characteristics, material structure, and electrochemical performance, thereby supporting the further development of sustainable biomass-derived composite electrodes for energy storage applications.

4. Conclusion

This study demonstrates the feasibility of converting banana peel waste into activated carbon and subsequently integrating it with MnO_2 through a hydrothermal synthesis route to produce biomass-derived composite electrodes for supercapacitor applications. Among the investigated compositions, MnO_2–BAC–1 exhibited the highest average specific capacitance of 108.87 F g^{-1} at a scan rate of 0.05 V s^{-1}, whereas MnO_2–BAC–0.5 showed the largest specific surface area (434.15 m^2 g^{-1}). These findings indicate that electrochemical performance was associated not only with specific surface area but also with the balance between pore characteristics and MnO_2 loading under the experimental conditions employed in this study.

The present work provides a preliminary experimental assessment of banana peel-derived MnO_2–carbon composites based on BET and cyclic voltammetry analyses. Accordingly, the observed relationships between pore characteristics and electrochemical behavior should be interpreted within the scope of the available experimental evidence. Further investigations incorporating X-ray diffraction (XRD), scanning electron microscopy (SEM/EDX), galvanostatic charge–discharge (GCD), electrochemical impedance spectroscopy (EIS), and long-term cycling stability are required to establish a more comprehensive understanding of the structure–property relationship and to support the future development of sustainable biomass-derived electrode materials for practical supercapacitor applications.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with language refinement, grammatical correction, and improvement of the readability of the manuscript. The tool was not used to generate, fabricate, or modify experimental data, results, or scientific findings. After using this tool, the authors reviewed and edited the content as necessary and take full responsibility for the content of the published article.

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.

Acknowledgments
The authors gratefully acknowledge Universitas Negeri Semarang for its academic and institutional support. The authors also acknowledge the Chemistry Laboratory, Faculty of Mathematics and Natural Sciences, Universitas Kristen Satya Wacana, and the Chemistry Laboratory, Universitas Gadjah Mada (UGM), for providing laboratory facilities and technical assistance during the experimental work. Appreciation is also extended to the laboratory staff and colleagues who contributed technical support throughout the study.
This research was conducted independently and received no research funding from any public, commercial, or non-profit funding agency. The authors gratefully acknowledge institutional support related to the dissemination and publication of this research.
This research contributes to the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) through the valorization of banana peel waste as a sustainable precursor for MnO_2–carbon composites.

References

[1] N. R. Putra, A. H. A. Aziz, A. N. M. Faizal, and M. A. Che Yunus, "Methods and Potential in Valorization of Banana Peels Waste by Various Extraction Processes: In Review," *Sustainability*, vol. 14, no. 17, p. 10571, Jan. 2022, doi: https://doi.org/10.3390/su141710571.

[2] Y. Hendronursito, W. Astuti, H. Sabarman, and I. Santoso, "A porous activated carbon derived from banana peel by hydrothermal activation two-step methods," *Int. J. Renew. Energy Dev.*, vol. 14, no. 2, pp. 322–331, Mar. 2025, doi: https://doi.org/10.61435/ijred.2025.60847.

[3] M. G. Tadesse, E. Kasaw, and J. F. Lübben, "Valorization of Banana Peel Using Carbonization: Potential Use in the Sustainable Manufacturing of Flexible Supercapacitors," *Micromachines*, vol. 14, no. 2, p. 330, Feb. 2023, doi: https://doi.org/10.3390/mi14020330.

[4] L. Sun, Y. Gong, D. Li, and C. Pan, "Biomass-derived porous carbon materials: synthesis, designing, and applications for supercapacitors," *Green Chem.*, vol. 24, no. 10, pp. 3864–3894, May 2022, doi: https://doi.org/10.1039/D2GC00099G.

[5] P. Manasa, S. Sambasivam, and F. Ran, "Recent progress on biomass waste derived activated carbon electrode materials for supercapacitors applications—A review," *J. Energy Storage*, vol. 54, p. 105290, Oct. 2022, doi: https://doi.org/10.1016/j.est.2022.105290.

[6] R. A. Qudsiyah *et al.*, "Green Hydrothermal Synthesis of rGO/MnO_2 Nanocomposites from Musa Paradisiaca Linn. Peel Extract for High-Performance Supercapacitor Electrodes," *Trends Sci.*, vol. 23, no. 7, Mar. 2026, doi: https://doi.org/10.48048/tis.2026.12607.

[7] D. P. N. Nahda *et al.*, "Synthesis of mesoporous carbon from banana peels with silica gel 60 as the hard templates," *RSC Adv.*, vol. 15, no. 6, pp. 4536–4545, 2025, doi: https://doi.org/10.1039/D4RA08322A.

[8] D. F. Pisceselia, R. E. D. Putri, and R. Gayatri, "Biomass-Derived Activated Carbon: Synthesis, Influencing Factors, and Applications in Environmental Remediation – A Review," *Chem. Eng. J. Storage CEJS*, vol. 6, no. 02, pp. 306–325, Apr. 2026, doi: https://doi.org/10.29103/cejs.v6i02.26954.

[9] A. Prayogatama, N. Nuryoto, and T. Kurniawan, "ELEKTRODA SUPERKAPASITOR DARI KARBON AKTIF BIOMASSA," *JST J. Sains Dan Teknol.*, vol. 11, no. 1, pp. 47–58, Feb. 2022, doi: https://doi.org/10.23887/jstundiksha.v11i1.42849.

[10] A. N. A. Saputra, W. Syafii, G. Pari, D. S. Nawawi, and A. Maddu, "BIOMASSA SEBAGAI MATERIAL ELEKTRODA SUPERKAPASITOR," vol. 40, no. 3, 2022, doi: https://doi.org/10.20886/jphh.2022.40.3. 189–202.

[11] A. Tripathy, S. Mohanty, S. K. Nayak, and A. Ramadoss, "Renewable banana-peel-derived activated carbon as an inexpensive and efficient electrode material showing fascinating supercapacitive performance," *J. Environ. Chem. Eng.*, vol. 9, no. 6, p. 106398, Dec. 2021, doi: https://doi.org/10.1016/j.jece.2021.106398.

[12] V. Packirisamy, R. Ariyamuthu, K. Thangavelu, V. V. Murugesan, and J. Rugmangathan, "Banana peel biomass–derived activated carbon for nickel ion removal and energy storage applications," *Biomass Convers. Biorefinery*, vol. 15, no. 21, pp. 27787–27799, Nov. 2025, doi: https://doi.org/10.1007/s13399-025-06703-5.
[13] O. J. Al-sareji, R. A. Grmasha, M. Meiczinger, R. A. Al-Juboori, V. Somogyi, and K. S. Hashim, "A Sustainable Banana Peel Activated Carbon for Removing Pharmaceutical Pollutants from Different Waters: Production, Characterization, and Application," *Materials*, vol. 17, no. 5, p. 1032, Feb. 2024, doi: https://doi.org/10.3390/ma17051032.
[14] F. Sajjad *et al.*, "Machine learning-driven optimization of biochar-based supercapacitors for sustainable energy storage: Mechanisms, trends, and perspectives," *Mater.*, vol. 11, p. 101971, Apr. 2026, doi: https://doi.org/10.1016/j.nxmate.2026.101971.
[15] P. Sohtun *et al.*, "Agriculture biomass-derived carbon materials for their application in sustainable energy storage," *Carbon Lett.*, vol. 35, no. 2, pp. 481–513, Apr. 2025, doi: https://doi.org/10.1007/s42823-025-00884-9.
[16] T. Feng, Y. Mo, B. Zou, C. Zhang, H. Chen, and G. Liu, "MnO2 nanowires anchored on biomass-derived porous carbon for enhanced supercapacitive performance," *Carbon Lett.*, vol. 35, no. 3, pp. 1139–1151, Jun. 2025, doi: https://doi.org/10.1007/s42823-024-00846-7.
[17] N. A. Surib *et al.*, "Microwave-Pyrolysed Rice Husk-Derived Activated Carbon as a Sustainable Anode Material for Lithium-Ion Half-Cell Batteries," *Adv. Sustain. Sci. Eng. Technol.*, vol. 8, no. 2, p. 02602027, Apr. 2026, doi: https://doi.org/10.26877/asset.v8i2.2740.
[18] P. H. Setyarini, H. S. Pembayun, D. H. Sulistyarini, N. H. Purwaningtyas, and F. G. U. Dewi, "Comparative Efficacy of Two Bamboo-Derived Activated Carbons for Hospital Wastewater Remediation," *Adv. Sustain. Sci. Eng. Technol.*, vol. 7, no. 3, p. 02503025, Aug. 2025, doi: https://doi.org/10.26877/asset.v7i3.1895.
[19] J. He, M. Li, X. Chen, Y. Wu, J. Sun, and X. Wen, "N-doped porous carbon derived from pomelo peel for high-performance supercapacitor," *J. Energy Storage*, vol. 99, p. 113183, Oct. 2024, doi: https://doi.org/10.1016/j.est.2024.113183.
[20] X. Zhu, Y. Zeng, X. Zhao, D. Liu, W. Lei, and S. Lu, "Biomass-Derived Carbon and Their Composites for Supercapacitor Applications: Sources, Functions, and Mechanisms," *EcoEnergy*, vol. 3, no. 3, p. e70000, 2025, doi: https://doi.org/10.1002/ece2.70000.
[21] S. A. Alghamdi *et al.*, "Biomass nanoarchitectonics of hierarchically porous activated carbon prepared from palm waste fibers for high-performance supercapacitor," *Sci. Rep.*, vol. 15, no. 1, p. 33269, Sep. 2025, doi: https://doi.org/10.1038/s41598-025-18633-3.
[22] A. Singh and A. K. Ojha, "Orange peel derived activated carbon for supercapacitor electrode material," *J. Mater. Sci. Mater. Electron.*, vol. 34, no. 11, p. 1003, Apr. 2023, doi: https://doi.org/10.1007/s10854-023-10418-6.
[23] S. Pramanik and S. De, "Green power from scraps: renovating fruit and vegetable waste into high-performance supercapacitor electrodes—a comprehensive review," *Waste Dispos. Sustain. Energy*, vol. 7, no. 4, pp. 777–802, Dec. 2025, doi: https://doi.org/10.1007/s42768-025-00253-2.
[24] D. Sridhar, S. Manikandan, and R. Gobi, "Bio-waste–derived activated carbon coupled with MnO_2/NiO nanocomposite for enhanced supercapacitor performance," *Ionics*, vol. 32, no. 3, pp. 3371–3385, Mar. 2026, doi: https://doi.org/10.1007/s11581-026-06967-5.
[25] R. Li *et al.*, "A comprehensive study on two types of supercapacitor composite electrodes comprising MnO2 and activated carbon nanofibers: Self-supporting membrane and ground powder," *J. Energy Storage*, vol. 92, p. 112196, Jul. 2024, doi: https://doi.org/10.1016/j.est.2024.112196.
[26] E. Taer, R. Taslim, Z. Aini, S. D. Hartati, and W. S. Mustika, "Activated carbon electrode from banana-peel waste for supercapacitor applications," *AIP Conf. Proc.*, vol. 1801, no. 1, p. 040004, Jan. 2017, doi: https://doi.org/10.1063/1.4973093.