WEP Warwick Evans Publishing

International Journal of Public Health and Medical Research
ISSN: 3006-7707 (Print), ISSN: 3006-3752 (Online) | Volume 6, Number 3, Year 2026
DOI: https://doi.org/10.62051/ijphmr.v6n3.09
Journal homepage: https://wepub.org/index.php/IJPHMR/index

Research Progress on Coffee Biomass Material Capacitors

Xurundong Kan [1,*], Jingwei Pu [2], Yaning Liu [3], Li Qiu [4]

[1] International Union Laboratory of China and Malaysia for Quality Monitoring and Evaluation of Agricultural Products in Yunnan, School of Biology and Chemistry, Pu'er University, Pu'er, Yunnan, China

[2] School of Education, Taylor's University, Subang Jaya, Selangor, Malaysia

[3] School of Tea (Pu'er), West Yunnan University of Applied Sciences, Pu'er 665000, China

[4] School of Architecture and Engineering, Yancheng Kindergarten Teachers college, Yancheng China

*Corresponding Author: kanxurundong@163.com

ABSTRACT

The increasing demand for sustainable energy storage solutions has driven research into eco-friendly materials, with coffee biomass emerging as a promising candidate due to its natural abundance and renewable characteristics. This review systematically examines the fundamental properties of coffee biomass-derived materials, highlighting their unique structural and chemical features that contribute to enhanced electrochemical performance. The application of these materials in capacitors demonstrates significant improvements in capacitance and cycling stability, attributed to their porous architecture and favorable surface chemistry. Furthermore, the integration of coffee-based components in energy storage devices showcases notable advancements in efficiency and environmental compatibility. The findings underscore the potential of coffee biomass as a viable alternative to conventional materials, offering both economic and ecological benefits. Future research directions emphasize the optimization of processing techniques and the exploration of hybrid systems to further elevate performance metrics, paving the way for broader implementation in next-generation energy technologies.

KEYWORDS

Coffee Biomass; Supercapacitors; Biomass-Derived Carbon; Energy Storage Materials; Sustainable Electronics

1. INTRODUCTION

The global transition towards sustainable energy systems is a critical challenge of the 21st century. This shift is driven by the urgent need to mitigate climate change, reduce reliance on fossil fuels, and meet the growing energy demands of modern society. Energy storage technologies, particularly capacitors, play a pivotal role in this landscape by enabling the efficient capture and release of energy from intermittent renewable sources like solar and wind. However, the widespread deployment of conventional energy storage devices is often hindered by factors such as high cost, reliance on scarce or toxic materials, and significant environmental impact from production to disposal. These challenges have spurred intensive research into finding alternative, eco-friendly materials that are abundant, renewable, and possess favorable electrochemical properties.

In this context, biomass-derived materials have emerged as a highly promising avenue. Utilizing waste biomass not only addresses the issue of material sustainability but also contributes to a circular economy by valorizing agricultural and industrial by-products. Among various biomass sources, coffee waste, primarily in the form of spent coffee grounds, has attracted considerable scientific interest by 2026. The massive global consumption of coffee generates millions of tons of waste annually, which is typically discarded in landfills, leading to methane emissions and environmental pollution. Transforming this abundant, low-cost, and renewable waste stream into high-value materials for energy storage represents a compelling opportunity with dual environmental and economic benefits.

The intrinsic properties of coffee biomass make it particularly suitable for capacitor applications. Its natural composition, rich in carbon, cellulose, lignin, and heteroatoms like nitrogen and phosphorus, provides an excellent precursor for producing porous carbon materials. Through controlled thermal treatment and activation processes, this waste can be converted into carbon structures with high surface area, tunable pore architecture, and beneficial surface chemistry. These structural features are directly linked to enhanced electrochemical performance in capacitors, facilitating efficient ion transport and charge storage. Early research, such as the pioneering work by PARK M. H. and subsequent studies, has demonstrated the feasibility of deriving nanoporous carbon nanosheets and mesopore-dominant activated carbons from coffee grounds, achieving significant improvements in capacitance and cycling stability compared to some commercial counterparts.

The motivation for this review stems from the rapid and multifaceted progress in this field over the past decade. By early 2026, research has evolved from proving basic feasibility to deeply understanding structure-property relationships and exploring advanced applications, including integration into self-powered systems. Despite this progress, a systematic synthesis that clearly outlines the fundamental rationale, key drivers, and defined research pathways is valuable for guiding future work, especially for students and newcomers to the field. This chapter aims to establish that foundational context.

Therefore, the primary objectives of this review are threefold. First, to provide a clear background on the global energy storage challenge and articulate the compelling motivation for exploring coffee biomass as a sustainable material solution. Second, to systematically examine the fundamental properties of coffee-derived materials that underpin their electrochemical functionality. Third, to critically analyze their application and performance in capacitors, highlighting both achieved advancements and existing limitations. Ultimately, this work seeks to consolidate current knowledge, underscore the potential of coffee biomass in contributing to greener energy technologies, and identify key directions for future research to overcome remaining barriers and enable broader implementation.

2. FUNDAMENTALS AND PROPERTIES OF COFFEE BIOMASS-DERIVED MATERIALS

2.1. Composition, Structure, and Pretreatment Methods of Coffee Biomass

Coffee biomass, primarily derived from spent coffee grounds, possesses a unique and advantageous composition that makes it an excellent precursor for high-performance carbon materials used in capacitors. Its natural structure, rich in carbon-based polymers and heteroatoms, provides a built-in template for creating porous architectures essential for electrochemical energy storage. Understanding this inherent composition and the initial pretreatment steps is fundamental to appreciating how a common waste product is transformed into a functional electrode material.

The primary components of coffee grounds are lignocellulosic materials, including cellulose, hemicellulose, and lignin. These biopolymers form a robust and complex three-dimensional network. Crucially, coffee biomass also contains significant amounts of lipids (oils), proteins, and a small percentage of minerals. The presence of these elements is a key differentiator. Proteins, for instance, are a natural source of nitrogen, while other compounds contribute phosphorus and potassium. This inherent heteroatom content is highly valuable, as it enables "self-doping" during subsequent thermal processing, where nitrogen and phosphorus atoms become incorporated into the carbon lattice without requiring external, often expensive, doping agents [1]. This self-doping enhances the material's surface chemistry and electronic properties, contributing to improved charge storage capacity.

The physical structure of raw coffee grounds is inherently porous at the microscopic level, a remnant of its cellular plant structure. This natural porosity acts as an initial template. However, to convert this raw biomass into a material suitable for capacitors, it must undergo pretreatment and a primary conversion step, typically pyrolysis. Pretreatment often involves simple but critical steps like thorough washing to remove impurities and oils, followed by drying and grinding to achieve a uniform particle size. This consistency is important for ensuring homogeneous reactions during the main thermal treatment.

The most common initial conversion method is carbonization through pyrolysis, where the dried biomass is heated in an inert atmosphere (like nitrogen or argon) to a high temperature. During this process, the volatile components (water, oils, and gases) are driven off, leaving behind a carbon-rich char. This char retains some of the original biomass structure but is still relatively low in surface area and not optimally porous for capacitor applications. The work by PARK M. H. et al. demonstrated this foundational step, showing that simple carbonization of coffee grounds could yield carbon nanosheets [2]. The lipids present in the grounds were found to play a significant role during pyrolysis, aiding in the formation of a rudimentary graphitic-like structure and contributing to the development of this nanosheet morphology. This stage establishes the basic carbon framework upon which more advanced porous structures are built through further activation processes, which are discussed in subsequent sections.

In summary, the viability of coffee biomass for energy storage begins with its favorable natural composition and structure. Its blend of lignocellulose for a carbon backbone, coupled with intrinsic heteroatoms for self-doping, provides a superior starting point compared to many other biomass sources. The initial pretreatment and pyrolysis steps are designed to preserve and begin refining these inherent advantages, transforming the waste material into a functional carbonaceous char ready for further enhancement. This foundational understanding directly supports the broader goal of developing sustainable and renewable energy storage devices from low-cost, environmentally friendly feedstocks [2][3].

2.2. Synthesis and Characterization Techniques for Coffee Biomass-Based Electrode Materials

Following the initial carbonization described in the preceding section, the transformation of coffee biomass into a high-performance electrode material requires precise synthesis and rigorous characterization techniques. The synthesis process primarily involves activation to develop the porous structure, while characterization methods are essential for understanding the resulting material's physical and chemical properties, which directly dictate its electrochemical performance.

The most critical step after pyrolysis is chemical activation, with potassium hydroxide (KOH) being the predominant activating agent. This process involves physically mixing the carbonized coffee char with KOH, typically at a specific mass ratio, followed by a second high-temperature treatment under an inert atmosphere. The KOH reacts aggressively with the carbon framework, etching away portions of the structure to create a vast network of pores. The activation temperature and the KOH-to-char ratio are the two most influential parameters. Higher temperatures and higher KOH ratios generally lead to more extensive etching, resulting in materials with significantly increased specific surface area and pore volume. Research has demonstrated that optimizing these conditions can yield activated carbons with specific surface areas exceeding 3000 m^2/g, far surpassing that of commercially available activated carbons [1]. The activation process not only creates porosity but also influences the pore size distribution. A balanced distribution of micropores (for high surface area) and mesopores (for efficient ion transport) is crucial for achieving both high capacitance and good rate capability in capacitors.

Other activation methods, such as using zinc chloride ($ZnCl_2$) or phosphoric acid (H_3PO_4), have also been explored. These agents work through different mechanisms, such as dehydration and cross-linking, and can result in materials with distinct pore structures and surface chemistry. For instance, H_3PO_4 activation is known to produce carbons with a higher proportion of larger mesopores and can introduce phosphorus-containing functional groups to the surface. The choice of activator is therefore a key design decision, allowing for the tailored synthesis of materials optimized for different electrolytes or device configurations.

Once synthesized, the coffee-derived carbon material must be thoroughly characterized. The primary physical characterization focuses on porosity and surface area, typically analyzed using nitrogen adsorption-desorption isotherms. This technique provides critical data on the specific surface area, total pore volume, and the detailed pore size distribution (micropores, mesopores, macropores). The presence of a hierarchical pore structure—combining micropores for charge storage and interconnected mesopores for ion transport—is a hallmark of high-performance electrode materials derived from coffee biomass.

Morphological characterization, using techniques like scanning electron microscopy (SEM) and transmission electron microscopy (TEM), reveals the material's physical form and microstructure. These images often show a highly porous, three-dimensional network with a honeycomb-like or interconnected sheet-like structure, which is a direct result of the unique composition of the coffee precursor and the activation process. This open architecture is highly beneficial for electrolyte infiltration and ion accessibility.

Chemical characterization is equally important. X-ray photoelectron spectroscopy (XPS) is used to determine the elemental composition and identify the chemical states of atoms on the material's surface. This analysis confirms the successful "self-doping" of heteroatoms like nitrogen and phosphorus from the original coffee biomass into the carbon lattice. The presence of these heteroatoms, often in the form of pyridinic-N, pyrrolic-N, or C–P bonds, enhances the material's surface polarity, improves wettability by the electrolyte, and can introduce additional pseudocapacitance, thereby boosting the overall charge storage capacity.

In summary, the journey from carbonized char to a functional electrode is governed by controlled activation processes that engineer the material's porosity. Concurrently, a suite of characterization techniques provides indispensable insights into the structural and chemical features created. This synthesis-characterization feedback loop is fundamental to understanding and optimizing coffee biomass-derived materials for capacitor applications, ensuring that the inherent advantages of the raw biomass are fully realized in the final electrode.

3. APPLICATION AND PERFORMANCE OF COFFEE BIOMASS MATERIALS IN CAPACITORS

3.1. Electrochemical Performance in Supercapacitors and Hybrid Capacitors

The electrochemical performance of coffee biomass-derived materials in supercapacitors and hybrid capacitors is a direct outcome of their unique structural and chemical properties, as detailed in previous synthesis and characterization sections. When employed as electrodes, these materials demonstrate a compelling combination of high capacitance, excellent rate capability, and long-term stability, positioning them as viable, sustainable alternatives to conventional carbonaceous materials.

In symmetric supercapacitors utilizing aqueous electrolytes such as potassium hydroxide, electrodes fabricated from activated coffee-derived carbons exhibit significantly enhanced specific capacitance. This improvement is primarily attributed to the material's ultra-high specific surface area and hierarchical pore structure. The abundant micropores provide extensive sites for electrostatic charge accumulation via the electric double-layer mechanism, while the interconnected network of mesopores facilitates rapid ion diffusion, enabling the device to maintain high capacitance even at elevated current densities. Furthermore, the inherent heteroatom doping, particularly nitrogen and phosphorus originating from the biomass itself, contributes additional pseudocapacitance through reversible surface redox reactions. This synergistic effect between double-layer and pseudocapacitive storage mechanisms results in a substantial overall boost in energy storage capacity [4]. These devices typically show impressive cycling stability, with minimal capacitance degradation over tens of thousands of charge-discharge cycles, owing to the robust and chemically stable carbon framework that withstands repeated ion insertion and de-insertion.

The performance extends effectively to organic electrolyte systems, which offer a wider operational voltage window. The tailored pore structure, especially a mesopore-dominant architecture, is critical here as it accommodates the larger organic ions and ensures efficient electrolyte wetting and ion transport. This design enables supercapacitors based on coffee biomass carbons to achieve high energy densities without sacrificing power performance. The natural heteroatom functional groups also enhance the electrode's compatibility with organic electrolytes, improving interfacial charge transfer.

In the realm of hybrid capacitors, which integrate a battery-type faradaic electrode with a capacitive carbon electrode, coffee-derived carbons serve as an excellent capacitive component. For instance, in zinc-ion hybrid capacitors, the porous carbon cathode paired with a metallic zinc anode combines high energy and power density [5]. The high surface area and favorable pore size distribution of the coffee-based carbon facilitate rapid zinc-ion adsorption and desorption, contributing to superior rate performance. The material's structural integrity is key to mitigating issues like cathode active site underutilization and ensuring long cycle life for the device. Similarly, in other asymmetric systems pairing the carbon with a pseudocapacitive metal oxide, the coffee biomass-derived electrode provides stable double-layer capacitance and fast kinetics, effectively complementing the faradaic electrode to broaden the device's voltage window and enhance its energy density.

Recent advancements by 2026 highlight ongoing optimization. Research focuses on fine-tuning the pore size distribution and heteroatom content to maximize performance in specific electrolytes and device configurations. The development of flexible and miniaturized devices also leverages the processability of these biomass-derived materials. Their demonstrated capability to power small electronics, such as light-emitting diodes and sensors, validates their practical application potential in portable and wearable energy storage systems. Overall, the electrochemical performance underscores the successful translation of coffee biomass's inherent advantages into functional, high-performance capacitors, offering a promising path for eco-friendly energy storage technology.

3.2. Comparative Analysis with Other Biomass-Derived and Conventional Electrode Materials

To comprehensively evaluate the viability of coffee biomass-derived carbons, it is essential to compare their performance with other prominent biomass precursors and conventional commercial electrode materials. This comparative analysis reveals both the competitive advantages and inherent limitations of coffee-based materials within the broader landscape of energy storage.

When benchmarked against carbons derived from other agricultural or industrial wastes, such as coconut shells, wood, or rice husks, coffee biomass often demonstrates superior or comparable electrochemical properties. A key differentiator lies in its natural chemical composition. Coffee grounds inherently contain significant amounts of nitrogen, phosphorus, and other heteroatoms, which facilitate "self-doping" during pyrolysis without the need for expensive external dopants. This intrinsic feature provides a distinct advantage over many other biomass sources that require additional processing steps to introduce similar functionality [1]. The resulting heteroatom-doped carbon framework from coffee not only enhances electrical conductivity but also contributes additional pseudocapacitance, leading to a higher overall specific capacitance in many reported studies. Furthermore, the specific thermal decomposition behavior of coffee biomass components, including lipids and proteins, often yields a favorable hierarchical pore structure with a balanced mix of micro-, meso-, and macropores. This structure is crucial for efficient ion transport and storage. While other biomasses can also produce high-surface-area carbons, the consistency and tunability of the pore architecture from coffee precursors, particularly through controlled activation processes, have been highlighted as a significant strength.

The comparison extends to conventional, industrially produced electrode materials like activated carbon from coal or petroleum pitch and synthetic graphenes. Commercial activated carbons are valued for their consistent quality, scalability, and moderate cost. However, coffee-derived carbons frequently surpass them in terms of specific surface area and specific capacitance in aqueous electrolytes, as evidenced by multiple studies. The environmental and economic benefits are starkly in favor of the biomass alternative. Coffee biomass utilizes a widely available waste stream, contributing to a circular economy and reducing dependence on fossil-based precursors. The production process, while requiring optimization for scale, aligns with green chemistry principles by valorizing waste. In contrast, the synthesis of high-performance materials like graphene often involves complex, energy-intensive methods and costly reagents, limiting their sustainability and cost-effectiveness for large-scale energy storage applications.

However, the analysis must also acknowledge current challenges. The performance of biomass-derived materials, including those from coffee, can exhibit batch-to-batch variability due to differences in raw material source and composition. Achieving the same level of product uniformity as established commercial materials remains an engineering hurdle. Moreover, while laboratory-scale results are promising, the pathway to cost-effective mass production and integration into commercial device manufacturing requires further development. The long-term stability under extreme conditions and in various electrolyte systems also needs continuous validation against industry standards set by conventional materials.

In the context of flexible and miniaturized electronics, the transformation of discarded biomass into functional materials presents a compelling narrative [6]. Coffee-derived carbons, with their tunable properties, can be processed into inks or composites for printed or flexible supercapacitors, offering a sustainable alternative to non-renewable carbon nanomaterials in this growing sector.

In summary, coffee biomass-derived carbons hold a competitive position. They offer a unique combination of high electrochemical performance, derived from self-doped heteroatoms and tunable porosity, alongside significant environmental and potential economic benefits. While challenges in standardization and scale-up persist, their advantages over many other biomass sources and conventional fossil-based carbons underscore their potential as a sustainable material platform for next-generation capacitors.

4. CONCLUSION

The comprehensive review presented in this paper establishes coffee biomass as a highly promising and sustainable precursor for advanced electrode materials in energy storage devices, particularly supercapacitors. The intrinsic properties of spent coffee grounds, including their natural abundance, renewable nature, and favorable chemical composition rich in carbon and heteroatoms, provide a solid foundation for developing high-performance carbons. Through controlled pyrolysis and activation processes, these waste materials can be transformed into porous carbon architectures with high specific surface area, advantageous pore size distribution, and beneficial self-doping with elements like nitrogen and phosphorus. These structural and chemical features directly translate into enhanced electrochemical performance, characterized by high specific capacitance, good rate capability, and excellent long-term cycling stability. The successful demonstration of these materials in powering small electronic devices underscores their practical viability. Furthermore, the environmental and economic advantages of valorizing a global waste stream into a valuable resource for energy technology are significant, aligning perfectly with the principles of a circular economy and sustainable development goals.

Looking ahead, several key research directions emerge as critical for translating this laboratory-scale promise into broader technological and commercial reality. Future efforts must prioritize the optimization and standardization of material synthesis protocols. While the basic pyrolysis and activation methods are established, achieving precise control over the final material's properties—such as pore hierarchy, degree of graphitization, and heteroatom doping configuration—remains a challenge. Advanced characterization techniques combined with data-driven approaches, like machine learning, could help establish more robust synthesis-structure-property relationships, reducing batch-to-batch variability and enabling the tailored design of carbons for specific applications.

Another crucial perspective involves moving beyond single-material development towards the design of integrated hybrid systems. The exploration of coffee-derived carbons in composite structures, such as combining them with conductive polymers, metal oxides, or other nanocarbons, could unlock synergistic effects leading to further performance enhancements, particularly in energy density. Research should also expand into novel device architectures, including flexible, wearable, and micro-supercapacitors, where the processability of biomass-derived carbons into inks or films is a key area for investigation.

Scaling the production process from the gram scale in laboratories to the kilogram or ton scale required for commercial applications represents a major frontier. Future work must address engineering challenges related to feedstock consistency, process energy efficiency, reactor design, and cost-effective activation methods to ensure the economic viability of large-scale manufacturing. Concurrently, comprehensive life-cycle and techno-economic analyses are needed to quantitatively validate the environmental benefits and cost competitiveness of coffee biomass-derived capacitors compared to conventional systems.

Finally, the integration of these materials into full energy storage systems and their testing under real-world operating conditions is essential. Long-term stability assessments in different climatic conditions, safety evaluations, and compatibility studies with various electrolytes and device packaging materials will provide the necessary data for industry adoption. By addressing these future perspectives, the field can advance from proving fundamental concepts to enabling the practical implementation of coffee biomass materials, thereby contributing meaningfully to the development of next-generation, eco-friendly energy technologies.

ACKNOWLEDGEMENT

This work was supported by the Scientific Research Fund of the Education Department of Yunnan Province (Grant No. 2023J1233): Preparation and Electrochemical Performance of Coffee Husk Biomass-Based Capacitor Electrode Materials.

REFERENCES

[1] Zixuan Guo. Activation of biomass-derived porous carbon for supercapacitors: A review [J]. “Chinese Chemical Letters”, 2024, (7):121-138.

[2] Meizhen Dai. Research progress on transition metal oxide based electrode materials for asymmetric hybrid capacitors [J]. “Chinese Chemical Letters”, 2020, (9):2177-2188.

[3] Fangqian Wang. Lignocellulosic biomass as sustainable feedstock and materials for power generation and energy storage [J]. “Journal of Energy Chemistry”, 2021, (6):247-280.

[4] Mingzhu Zhong. Carbon nanomaterials and their composites for supercapacitors [J]. “Carbon Energy”, 2022, (5):950-985.

[5] Qing Wang. Carbon nanomaterials for aqueous zinc-ion capacitors: recent progress, challenges, and perspectives [J]. “Rare Metals”, 2024, (12):6255-6287.

[6] Sijia Bao. Transformation of discarded biomass into value-added flexible electronic materials [J]. “Green Energy & Environment”, 2025, (3):452-470.