Activated carbon from hazelnut bark-based biomaterial as an electrode material for supercapacitors

Aktivirani ugljenik dobijen iz biomaterijala na bazi kore lešnika kao elektrodni materijal za superkondenzatore

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Abstract

The growing demand for sustainable energy storage solutions drives the search for eco-friendly and low-cost electrode materials for supercapacitors. This study presents a sustainable approach for converting discarded hazelnut bark-based biocomposite into activated carbon (AC). The biocomposite was chemically activated with KOH at a mass ratio of 1:3. The mixture was then thermally treated under a nitrogen atmosphere in two stages: initially heated at 2 °C/ min to 500 °C and held for 1 h, followed by heating at 5 °C min^{-1} to 800 °C with an additional 1 h retention time. Electrochemical performance was investigated by cyclic voltammetry (CV) at various scan rates in 0.5 M H_2SO_4. The CV curves show a nearly rectangular shape, indicating that the charge storage mechanism is predominantly governed by electric double-layer capacitance. These findings demonstrate that hazelnut bark-based biocomposite represents a sustainable and efficient precursor for producing high-performance activated carbons, offering a promising alternative to conventional electrode materials in supercapacitors and contributing to environmentally responsible energy storage technologies.

Keywords: *Biomass-derived carbon; porous carbon; KOH activation*

Izvod

Rastuća potražnja za održivim rešenjima za skladištenje energije podstiče razvoj ekološki prihvatljivih i ekonomičnih elektrodnih materijala za superkontenzatore. U ovom radu je prikazan održiv pristup za konverziju odbačenog biokompozita na bazi kore lešnika u aktivirani ugljenik (AC). Biokompozit je hemijski aktiviran pomoću KOH u masenom odnosu 1:3, a zatim termički tretiran u atmosferi azota u dva koraka: u prvom koraku je zagrevan brzinom od 2 °C/min do 500 °C uz zadržavanje od 1 h, a potom zagrevan brzinom od 5 °C/min do 800 °C uz dodatno zadržavanje od 1 h. Elektrohemijska svojstva su ispitivana metodom ciklične voltametrije (CV) pri različitim brzinama skeniranja u rastvoru 0,5 M H_2SO_4. CV krive pokazuju približno pravougaoni oblik, što ukazuje na to da je mehanizam skladištenja naelektrisanja pretežno zasnovan na kapacitivnosti dvojnog sloja. Ovi nalazi pokazuju da biokompozit na bazi kore lešnika predstavlja održiv i efikasan prekurzor za

dobijanje aktiviranih ugljenika, koji mogu služiti kao obećavajuća alternativa konvencionalnim elektrodnim materijalima u superkondenzatorima i doprineti razvoju ekološki odgovorne tehnologije skladištenja energije.
Ključne reči: *ugljenik dobijen iz biomase; porozni ugljenik; aktivacija sa KOH*

Introduction

The increasing global demand for efficient and sustainable energy-storage solutions has become a major driving force behind contemporary research in electrochemical materials [1]. Among the available technologies, supercapacitors, also known as electric double-layer capacitors (EDLCs), are particularly promising due to their high power density, outstanding cycling stability, and rapid charge–discharge capability [2]. These attributes make them well-suited for applications requiring instantaneous energy delivery, including electric vehicles, hybrid propulsion systems, and regenerative energy technologies.

Activated carbons (ACs) currently dominate the commercial supercapacitor market as electrode materials because of their high specific surface area, well-developed porosity, and relatively low production cost [3]. Nevertheless, conventional methods for producing ACs often depend on non-renewable precursors and chemically intensive processes that are not fully aligned with the principles of green chemistry or sustainable manufacturing. Consequently, the search for environmentally friendly and economically viable precursors for high-performance carbon materials has intensified in recent years [4].

Biomass has emerged as a highly attractive renewable resource for the synthesis of activated carbon, offering advantages such as reduced environmental burden and decreased fabrication costs [5]. Agricultural residues are especially promising due to their abundance, low cost, and status as significant agronomic waste. Their valorization not only mitigates environmental pollution but also supports circular-economy principles [6].

This study presents a sustainable and efficient strategy for converting hazelnut bark-based derived biowaste into high-performance activated carbon. The approach involves carbonization followed by potassium hydroxide (KOH) activation at 800 °C, aimed at producing a highly developed microporous structure [7]. This method enables the fabrication of porous carbon materials with high specific surface area and tunable pore distribution, which are key determinants of electrochemical performance in EDLC electrodes.

Previous studies have demonstrated that various biomass-derived carbon materials can exhibit outstanding electrochemical performance [7,8]. These findings clearly indicate that carbon materials synthesized from agricultural waste streams can be highly competitive with, and in some cases superior to, conventional electrode materials.

Although materials such as reed and kapok have been explored, hazelnut biocomposite, as a widely available agricultural waste, remains an underexplored resource for the synthesis of AC electrodes. Building on this foundation, the present work focuses on developing a sustainable and efficient pathway for converting hazelnut biocomposites into high-performance activated carbon (AC). A straightforward yet effective synthesis approach was employed, consisting of carbonization followed by potassium hydroxide (KOH) activation at 800 °C. This route promotes the formation of a well-developed microporous network, which is essential for achieving effective electric double-layer charge storage [9].

Materials and Methods

Preparation of the activated carbon

Activated carbon (AC) was synthesized through chemical activation of discarded hazelnut-based biomass generated during the production of biomass-based bricks (Figure 1), using potassium

hydroxide (KOH, Sigma-Aldrich), followed by high-temperature carbonization. The milled biocomposite precursor was mixed with KOH at an optimal mass ratio of 1:3 (biocomposite:KOH). The mixture was thoroughly homogenized and subsequently dried at 100 °C for 6 h to remove residual moisture and promote uniform alkali impregnation. The impregnated precursor was placed in a tubular furnace and subjected to thermal treatment under a constant flow of high-purity nitrogen to maintain an inert atmosphere and carry away volatile decomposition products [10]. The temperature was increased at a heating rate of 5 °C min^{-1} up to 800 °C, followed by an isothermal hold for 1 h to complete carbonization and chemical activation. After natural cooling to room temperature under N_2, the resulting black powder was washed thoroughly to remove residual KOH and associated inorganic species. The washing procedure involved treatment with 0.1 M HCl, followed by repeated rinsing with distilled water until the filtrate reached a neutral pH (approximately 6.5). The final product was dried at 105 °C to constant mass.

Figure 1. *Discarded hazelnut-based biomass used as a precursor for activated carbon.*

Electrochemical studies

The basic electrochemical characteristics of the synthesized samples were investigated using cyclic voltammetry (CV). The electrochemical analysis was conducted in a three-electrode system comprising a platinum wire (counter electrode), a saturated calomel electrode (SCE) (reference electrode), and the working electrode, all immersed in an aqueous 0.5 M H_2SO_4 electrolyte at ambient temperature. Measurements were performed using a Bio-Logic SP200 potentiostat/galvanostat (Bio-Logic SAS, Grenoble, France). The working electrode was prepared by first dispersing 3 mg of the alkali-treated carbon per 1 mL H_2O, which was subsequently homogenized via ultrasonic treatment (40 kHz, 70 W) for 1 h. A volume of 7 µl of this suspension was drop-cast onto a glassy carbon (GC) disk electrode (diameter 0.5 cm) and dried at room temperature (24 °C). To ensure structural stability and adhesion of the active layer, the dried film was covered with a protective layer of Nafion binder, prepared from a 1:100 volume ratio dilution of 10 mass % Nafion solution in isopropanol/water with water. Cyclic voltammetry was performed at various scan rates (400, 300, 200, 100, 20 and 5 mV s^{-1}) to assess rate capability.

Results and Discussion

The CV curves recorded for the activated carbon at various scan rates are shown in Figure 3.

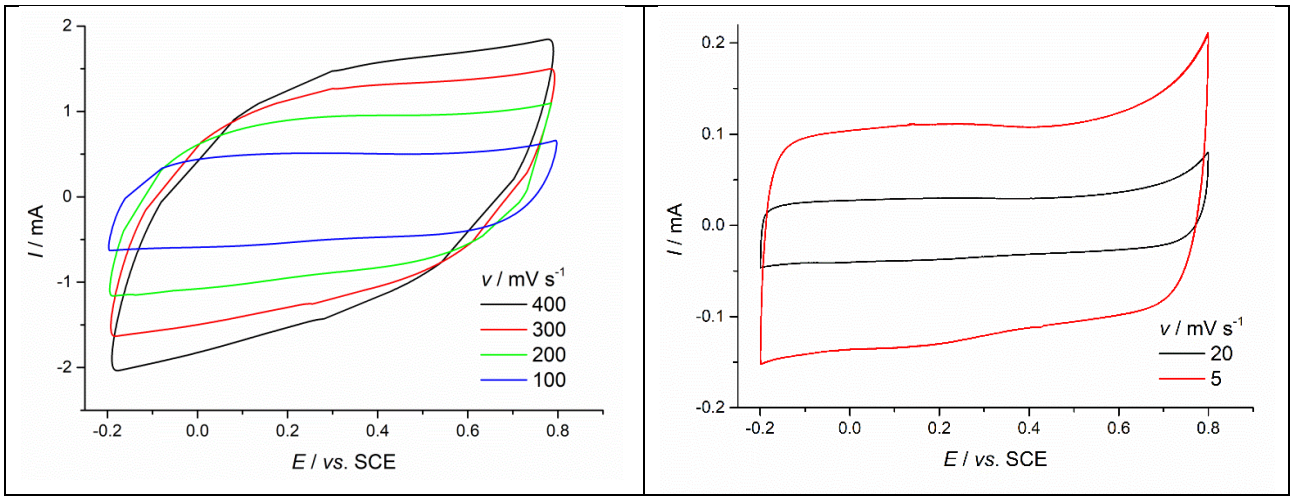

Figure 3. *CVs of activated carbon at a) high and b) low scan rates. Electrolyte: N_2-deaerated 0.5 M H_2SO_4*

The CV curves recorded for the activated carbon at both low and high scan rates (Figure 3) exhibit a characteristic quasi-rectangular profile, typical for carbon-based materials dominated by the electric double-layer capacitance (EDLC) mechanism [2]. Such a shape indicates the predominance of rapid and reversible ion adsorption/desorption processes occurring at the electrode–electrolyte interface, with minimal contribution from faradaic reactions. As the scan rate rises, the current values correspondingly become higher, reflecting the linear relationship expected for ideal capacitive behavior. At higher sweep rates, a slight tilting of the curves becomes evident, indicating increased resistive contributions and some limitations in ion transport within the pore structure. Nevertheless, the overall quasi-rectangular contour is largely preserved, suggesting that the pore structure of the activated carbon, particularly its accessible surface area and well-developed network of micro- and mesopores, remains sufficiently open to enable fast ion movement. The maintenance of the curve shape under dynamic conditions indicates that the electrode material is capable of rapid charge propagation within its porous framework. This is a key indicator of good rate capability, implying that ions can efficiently diffuse throughout the pore channels without severe diffusion limitations, even when the system is subjected to high polarization rates. In practical terms, such behavior is desirable for high-power supercapacitor applications, where the device must respond quickly to fluctuations in current demand.

Furthermore, the absence of pronounced redox peaks across all scan rates confirms that the capacitance arises predominantly from electrostatic charge storage rather than pseudocapacitive surface reactions. This purity of the EDLC response is consistent with highly porous, chemically stable carbon materials and suggests that the activation process has generated a surface chemistry favorable for efficient double-layer formation without introducing significant electroactive functional groups.

Conclusion

In this study, activated carbon derived from discarded hazelnut bark-based biocomposite was successfully synthesized through KOH activation and high-temperature carbonization. The resulting material exhibited a well-developed porous structure capable of supporting efficient electric double-layer charge storage, as evidenced by the quasi-rectangular CV curves. These electrochemical results, together with the sustainable and low-cost origin of the precursor, demonstrate that hazelnut bark-based biocomposite is a highly promising feedstock for producing high-performance activated carbons. By converting agricultural and biomass waste into efficient supercapacitor electrode materials, this approach not only reduces environmental impact but also supports the development of

greener energy storage technologies. Overall, the findings validate the potential of this bio-derived activated carbon as an effective and environmentally responsible alternative to conventional carbonaceous electrodes in modern supercapacitor systems.

Acknowledgments

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