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RESEARCH

Tailoring Surface Chemistry of *Manilkara zapota* Seed Derived Activated Carbon for the Fabrication of Energetic Zinc-Ion Hybrid Supercapacitor

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Abstract

Integrating a battery-type electrode with a capacitive-type electrode in a hybrid configuration has become an attractive strategy to improve the device's overall energy density without compromising power density. The hybrid supercapacitor (HSC) based on metal ions, such as Li^+, Na^+, and K^+, demands an anhydrous environment for its fabrication. Moreover, the use of non-aqueous electrolytes for their operation can significantly increase fabrication costs and safety risks. To overcome these key issues, an eco-friendly HSC is fabricated using a multivalent Zn with a high specific capacity and a low redox potential (−0.76 V *vs*. SHE) as the anode in an aqueous medium. The N-doped porous activated carbon (N-ACMZ-700) derived from the seeds of Manilkara zapota, a natural biomass, and pyrolyzed at 700 °C, is used as a cathode material. The reversible ion adsorption/desorption at the N-ACMZ-700 cathode and Zn^{2+} stripping/plating at the Zn-anode enable the Zn//N-ACMZ-700 hybrid capacitor to deliver a high specific capacitance of 356 F g^{-1} at 0.1 A g^{-1}. Benefiting from the synergistic merits of excellent structural features of N-ACMZ-700 cathode material and metallic Zn-anode, resulting Zn//N-ACMZ-700 HSC shows an excellent energy storage performance, including high energy density of 178 Wh kg^{-1} @ 0.1 A g^{-1}, a maximum power density of 9.44 kW kg^{-1}, and outstanding cycling stability up to 10,000 galvanostatic charge/discharge cycles with ~90% of initial capacity retention. Electrochemical impedance spectroscopy results demonstrate that the N-ACMZ-700-based Zinc-HSC exhibits low internal resistance, rapid charge-transfer kinetics, and efficient ion diffusion pathways, which collectively contribute to its high-power capability and stable electrochemical performance.

Keywords Activated Carbon · Aqueous Supercapacitors · *Manilkara Zapota* · Hybrid Supercapacitor · Zn-ion Supercapacitor

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Introduction

Energy storage systems are increasingly crucial in today's world, particularly as renewable energy sources, such as solar and wind power, expand rapidly. Hence, there is an immediate need for advances in the development of efficient, safe, and environmentally sustainable energy storage systems [1–4]. Today, energy storage devices such as batteries and supercapacitors (SCs) have emerged as key technologies to transform energy storage capabilities across multiple sectors. Batteries are known for their high energy density, making them ideal for applications that require sustained energy output [5, 6]. In contrast, SCs possess remarkably high-power densities, enabling ultrafast charging and discharging, as well as good cycle life [7–9]. However,