Green and Sustainable Energy Storage Using Borax–Chitosan Hydrogel Electrolytes in EDLCs

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Abstract

The growing concerns over chemical pollution and the rapid accumulation of microplastics necessitate the development of sustainable and high-performance energy storage systems. Among these, electrical double-layer capacitors (EDLCs) stand out for their remarkable cycling stability, yet their practical utility is often limited by low energy density and the reliance on environmentally harmful liquid electrolytes. In this work, we present a facile, eco-friendly synthesis of a borax-crosslinked chitosan hydrogel membrane electrolyte (BCCHME). Borax simultaneously facilitates ionic and covalent crosslinking, thereby reinforcing the mechanical strength and enhancing ion mobility within the membrane. The optimized BCCHME demonstrates 182 % water uptake, 14.65 % dissolution ratio, and a semi-crystalline framework with 16.59 % crystallinity, supported by a uniform porous morphology. Structural verification through FTIR confirms the dual crosslinking, while elemental mapping reveals the presence of Na, B, C, N, and O. Electrochemical evaluation shows a high dielectric constant, ionic conductivity of 7.03×10^{-4} S cm^{-1}, ion transference number of 0.93, diffusion coefficient of 4.19×10^{-9} m^2s^{-1}, and electrochemical stability up to 2.24 V. A solid-state EDLC fabricated using BCCHME and Black Pearls carbon (BPC) electrodes achieves an areal capacitance of 378 mF cm^{-2}, an energy density of 52.5 µWh cm^{-2}, and a power density of 5000 µW cm^{-2} at 5 mA cm^{-2}. The device also exhibits outstanding cycle life, maintaining performance for 53,000 cycles at 2 mA cm^{-2} and 30,000 cycles at 5 mA cm^{-2}. Furthermore, a prototype configuration powered a 1 V LED for 1.83 minutes. Overall, this study demonstrates BCCHME as a biodegradable and non-toxic hydrogel electrolyte, merging sustainability with practical device-level performance for next-generation supercapacitors.