Esterified Spent Tea Leaves–Derived Porous Hard Carbon for Sodium-Ion Battery Anodes

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Abstract:

Sodium-ion batteries are considered a promising alternative to lithium-ion systems due to their low cost and abundant resources. Biomass-derived hard carbon has emerged as a competitive anode material, with ongoing progress toward practical applications.

Compared with conventional wood-based precursors, waste tea leaves possess naturally porous structures, complex frameworks, and abundant heteroatoms, offering unique advantages for hard carbon design. With the rapid growth of the beverage industry, large-scale collection of tea waste has recently become feasible, making it a sustainable and scalable carbon source.

In this work, an esterification strategy using maleic anhydride was employed to modify tea-waste-derived hard carbon, enabling simultaneous optimization of pore structure, surface chemistry, and interlayer spacing. By controlling the reaction time, the optimized sample (2TM-1400) exhibited a well-developed hierarchical micro–mesoporous structure (8–20 nm) and enlarged interlayer spacing. Electrochemical results demonstrate that 2TM-1400 achieves enhanced capacitive contribution, improved initial coulombic efficiency, and stable long-term cycling performance. GITT analysis further confirms accelerated Na^+ diffusion kinetics. The sodium storage mechanism can be attributed to a synergistic adsorption–intercalation–pore-filling process.

In addition, a vacuum distillation strategy was proposed to recover excess maleic anhydride, improving reagent utilization and process sustainability. This work provides a

scalable and environmentally friendly pathway for converting waste biomass into high-performance energy storage materials.

Keywords: Spent tea leaves; Esterification modification; Hard carbon anode; Sodium-ion battery