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Viewpoint

Customizing Biochar Formulations: Enabling Sustainable and High-Performance Electrochemical Energy Storage Devices

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Efficient and secure energy practices are crucial in combating climate change. Policymakers must balance immediate actions with long-term strategies for a resilient energy system. To meet the 1.5°C target for net-zero CO_2 emissions by 2050, the International Renewable Energy Agency (IRENA) forecasts a 12-fold increase in renewable electricity capacity from 2020 levels, requiring an additional 1066 GW annually from 2023. This transition relies on renewable adoption, energy efficiency, and electrification. While electrification of industry and transport is vital, bioenergy will be essential for decarbonizing sectors where electrification is impractical. By 2050, modern biomass conversion technologies—such as biofuels, biogas, and biomass-based electricity—are expected to contribute 16% of total final energy consumption, while hydrogen will account for 14%.[1,2] Bioenergy's share in the total energy mix is expected to rise significantly, with demand reaching 56 exajoules (EJ) by 2050, according to the IRENA World Energy Transitions Outlook 2023. This demand will be split between energy production (power and heat) and feedstock for bio-based chemicals and materials.

Biomass stands out as a renewable resource that offers a sustainable and versatile feedstock for various applications. Carbon materials derived from biomass, such as biochar, activated biochar, carbon nanotubes, and graphene, hold significant potential to revolutionize electrochemical energy storage systems, including batteries and supercapacitors, due to their high surface area, conductivity, and sustainability.[3−6] Their adjustable surface chemistry, high conductivity, and chemical durability make these materials ideal for enhancing energy storage devices. In lithium-ion batteries (LIBs), carbon-based materials facilitate efficient lithium insertion and release at the anode. Carbon black improves power by strengthening the electronic network in porous electrodes, while graphite and hard carbons are key active materials in the anodes of LIBs and sodium-ion batteries.[7,8] In supercapacitors, carbon-based materials like activated carbon and carbon nanotubes provide a large surface area, enabling rapid energy storage and release for high-power applications.[9]

Biomass, primarily made up of carbon, hydrogen, and oxygen, is an abundant renewable resource derived from agriculture, forestry, fisheries, and waste streams.[10] Photosynthesis captures 60 billion metric tons of carbon annually, with about 10% becoming residual biomass.[11] By converting 6 billion metric tons of this carbon through processes like pyrolysis, we could produce 2 billion metric tons of biochar yearly for many different uses, including energy storage. This could help create a circular carbon economy. Companies like Airex Energy, Anellotech, and Biochar Now, LLC are working to scale biomass-derived carbon production, using methods like pyrolysis and hydrothermal carbonization.[12] Each method has unique strategies but needs better batch consistency and stability. High production costs and biochar's heterogeneous nature are key concerns.

We believe that the successful integration of biochar into the market for electrochemical energy devices requires a comprehensive and systematic approach with the five critical elements: 1) recognizing and utilizing strategic waste biomass specific to each region, 2) prioritizing cost-effective operations (focusing on optimizing pyrolysis, recovering energy, scaling up processes, and minimizing chemical treatments), 3) adopting sustainable approaches for electrode design, 4) tailoring formulations (involving identifying the specific electrochemical energy storage devices (EESDs), then optimizing key properties like conductivity, porosity, and heteroatom quantities through controlled processes to maximize performance), and 5) conducting comprehensive life cycle assessments (LCAs) and techno-economic analyses (TEAs). Each stage is vital to ensure the viability and sustainability of biochar-based solutions in energy storage applications.

The performance of biochar is heavily influenced by the specific system in which it is applied.[4,13,14] While unmodified biochar may exhibit superior performance in one system,[15] activation of biochar can yield significant improvements in another.[16] A thorough understanding of the properties of both activated and nonactivated biochar from various feedstocks, and their respective influences on the capacity and longevity of EESDs, is essential. Activated biochar, with its larger surface area and enhanced electrochemical properties, often demonstrates superior performance in applications such as supercapacitors and batteries.[6,16,17] Conversely, nonactivated biochar, despite lower conductivity and porosity, can still yield promising results depending on the biomass source and specific application.[18] The strategic selection of feedstocks and activation methods is vital for optimizing biochar's electrochemical characteristics, making it a sustainable and effective material for EESDs.[19] Rather than focusing solely on feedstock types, emphasis should be placed on engineering biochar to meet the specific requirements of each application. Key properties must be determined before adjusting pyrolysis or other processes. Since activated biochar is resource intensive to produce, unprocessed biochar, with its lower environmental impact, should be given more consideration.

Integrating biochar into existing energy storage technologies is crucial for its commercial success. Biochar must offer high energy density, long cycle life, and versatility in applications like catalysis, adsorption, and environmental remediation.[20] Advancing feedstocks (e.g., forestry byproducts, algal biomass)[21] and techniques (e.g., advanced pyrolysis, activation)[22] will broaden biochar's potential, especially for next-generation energy storage. For instance, biochar holds promise for applications in emerging systems such as lithium−metal-free sulfur (LiMFS) batteries[18] and solid-state batteries (SSBs).[23] In our recent published study,[15] we proposed a sustainable LiMFS battery design, with spent ivy biomass undergoing a one-step carbonization as the anode material and sulfur as the cathode. This design effectively eliminates the direct use of metallic lithium and other critical raw materials such as cobalt, nickel, graphite, and manganese in battery production. Furthermore, in SSB technology, biochar can serve as a passivation layer on the lithium metal surface, mitigating reactions between the anode and solid electrolyte,[24] or it can be integrated as an additive in the cathode electrode.[25] Alternatively, in the context of Generation 4a batteries, biochar may be employed together with silicon in Si/C composite anodes to mitigate silicon pulverization issues during cycling.[26] Further exploration of the eco-friendly solvents for the coating of the biochar electrodes, in contrast to toxic solvents such as N-methyl-2-pyrrolidone (NMP), is imperative for both supercapacitors and batteries. Achieving high-mass loading electrodes remains a primary focus in advancing this endeavor.

Biochar LCAs and TEAs are crucial for industry and policymakers. Mapping sidestreams—considering availability, environmental impact, market value, and composition—is essential. Interdisciplinary collaboration can speed up the shift from lab prototypes to commercial biochar solutions, turning waste into high-performance materials for a sustainable energy future.

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Notes

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