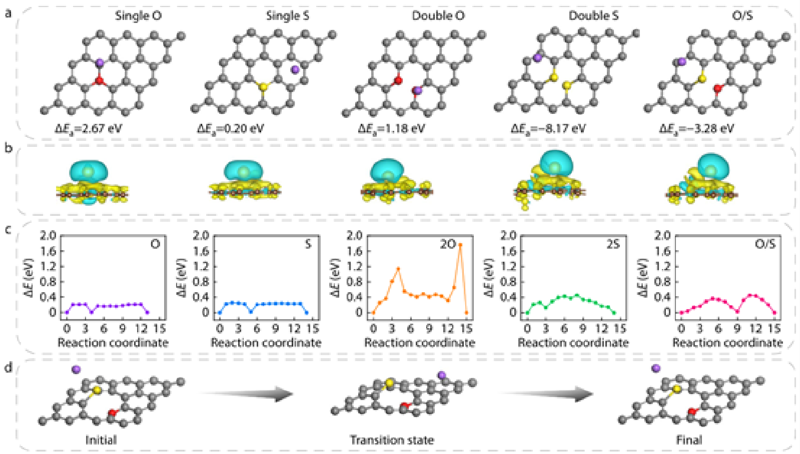
A molecular fix for sodium-ion batteries' weakest link



Theoretical investigation of heteroatom-doped HC models.

GA, UNITED STATES, February 27, 2026 /EINPresswire.com/ -- Sodium-ion batteries are emerging as a promising alternative to lithium-based systems, but their performance has long been limited by unstable anode materials and poor initial efficiency. A recent study addresses this challenge by redesigning hard carbon at the molecular level, enabling precise control over its internal pore structure and sodium storage behavior. By combining intramolecular doping engineering with a targeted presodiation strategy, the research achieves both high reversible capacity and exceptional long-term stability. The approach not only improves sodium-ion adsorption and transport but also suppresses irreversible sodium loss during early cycling, offering a practical pathway toward durable, high-efficiency sodium-ion batteries.

As renewable energy deployment accelerates worldwide, large-scale energy storage technologies must become more affordable, safer, and resource-efficient. Sodium-ion batteries stand out because sodium is abundant and inexpensive, yet their commercialization is hindered by the lack of high-performance anode materials. Hard carbon is widely regarded as the most promising anode candidate, but its performance strongly depends on poorly controlled internal pores and defect structures. Excessive open pores often trigger electrolyte decomposition, unstable interfacial layers, and severe initial capacity loss. Based on these challenges, it is necessary to conduct in-depth research on how molecular-level precursor design and interfacial regulation can jointly enhance hard carbon anodes.

Researchers from Jiangxi Normal University and Gannan Normal University report a new strategy to stabilize hard carbon anodes for sodium-ion batteries, published online on November 19, 2025, in Chinese Journal of Polymer Science. The study introduces intramolecular heteroatom doping within polymer precursors, followed by controlled chemical presodiation, to engineer closed-pore structures and robust interfacial layers. This synergistic design significantly improves reversible capacity, initial Coulombic efficiency, and long-term cycling stability, addressing key bottlenecks that have constrained sodium-ion battery development.

The research begins by designing polymer precursors with specific functional groups—such as sulfonyl, ether, and carbonyl units—embedded directly within aromatic backbones. During carbonization, these intramolecular dopants decompose in a controlled manner, generating abundant closed nanopores while avoiding excessive surface area. Structural analyses, including X-ray diffraction, Raman spectroscopy, and small-angle X-ray scattering, reveal that the optimized hard carbon contains a high volume of closed pores that favor low-voltage sodium storage.

Electrochemical tests demonstrate that the optimized material delivers a reversible capacity of 307.9 mAh g^{-1}, with strong rate capability and minimal structural degradation. However, the researchers identified that irreversible sodium loss during initial cycling still limited practical efficiency. To address this, a brief chemical presodiation step was introduced, supplying sodium in advance and pre-forming a stable interfacial layer. As a result, the initial Coulombic efficiency increased dramatically to 94.4%.

Long-term tests further show that the presodiated hard carbon retains 93.6% of its capacity after 3,000 charge–discharge cycles. Microscopic and spectroscopic analyses confirm the formation of a thin, dense, and sodium-fluoride-rich interphase, which enhances ion transport while suppressing electrolyte decomposition.

"This work shows that the performance limits of hard carbon are not fixed but can be fundamentally reshaped through molecular design," said one of the study's corresponding authors. "By controlling how heteroatoms are incorporated within polymer precursors, we can regulate pore formation from the inside out. When combined with presodiation, this strategy not only boosts efficiency but also stabilizes the electrode–electrolyte interface over thousands of cycles. The results suggest a scalable and versatile route for building next-generation sodium-ion battery anodes."

The findings offer important implications for the future of large-scale energy storage, particularly in grid applications where cost, safety, and durability are critical. The molecular-level engineering strategy demonstrated in this study can be extended to other polymer-derived carbons and potentially adapted for potassium-ion or multivalent battery systems. By simultaneously improving capacity, efficiency, and lifespan, the approach brings sodium-ion batteries closer to commercial viability. More broadly, the work highlights how precursor chemistry and interfacial control can be integrated to overcome long-standing materials challenges in electrochemical energy storage.

References

DOI
10.1007/s10118-025-3461-0

Original Source URL
https://doi.org/10.1007/s10118-025-3461-0

Funding information
This work was financially supported by the Ministry of Industry and Information Technology of China, the National Natural Science Foundation of China (No. 52403263), Technology Research Project of Jiangxi Provincial Department of Education (No. GJJ2200385), and Jiangxi Provincial Natural Science Foundation (Nos. 20244BCE52213, 20242BAB23031 and 20232BAB204006).

Lucy Wang
BioDesign Research
email us here
