Suppressing Dendrite Formation in Zinc–Air Batteries via Bi_2O_3-Modified Zinc Powder Anodes with Bio-Derived Binders

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Aqueous rechargeable zinc–air batteries (AZABs) have gained significant attention as next-generation green energy storage systems owing to their high theoretical specific capacity (~820 mAh g^{-1}), large volumetric energy density, cost-effectiveness, and environmentally benign components. These features make them particularly attractive for grid-scale storage and portable electronic applications [1]. However, the widespread adoption of AZABs remains hindered by critical limitations associated with the zinc anode, such as hydrogen evolution reactions (HER), surface passivation due to the formation of insulating ZnO layers, morphological instability during cycling, and, most importantly, dendritic zinc growth that can lead to short circuits and rapid capacity fading.

To address these challenges, considerable research has focused on replacing zinc foil with zinc powder-based anodes, which offer several advantages. The high surface area of zinc powder reduces local current density, thereby suppressing dendrite formation and decreasing overpotentials. Moreover, powder-based electrodes enable better structural tunability and more uniform zinc utilization. However, simply using zinc powder is not sufficient. Additives that can improve charge transport, inhibit passivation, and regulate zinc deposition are crucial for achieving high performance and long-term reversibility [2-4].

In this study, we developed a tunable zinc powder anode incorporating functional additives and a bio-derived binder system aimed at enhancing the rechargeability and stability of AZABs. The anode composite consists of nanosized zinc powder as the active material, ZnO to assist in uniform zinc dissolution/deposition, Bi_2O_3 for dendrite suppression and passivation resistance, and carbon black to improve the electronic conductivity. A unique feature of this work is the use of natural gum as a green, cost-effective binder, replacing synthetic polymer matrices. This approach simplifies the electrode architecture and promotes sustainable materials design.

The composite mixture was homogenized and thermally treated at 200 °C before being coated onto a steel mesh current collector. Structural characterization was performed using X-ray diffraction (XRD) and scanning electron microscopy (SEM), while surface chemistry was examined through energy-dispersive X-ray spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS), and Raman spectroscopy. These analyses confirmed the homogeneity of additive distribution and the morphological stability of the anode after cycling.

Electrochemical performance was evaluated in a custom-built zinc–air battery configuration employing a 6 M KOH electrolyte and a bifunctional high-entropy perovskite oxide catalyst supported on carbon cloth as the air cathode. Compared to zinc foil-based cells, the zinc powder anode demonstrated significantly higher gravimetric power density and specific capacity. Charge-discharge profiles at both low (1 mA cm^{-2}) and high (5 mA cm^{-2}) current densities revealed enhanced cycling stability and reduced polarization. SEM images of cycled anodes showed markedly lower dendritic features in the Bi_2O_3-modified samples, supporting the effectiveness of bismuth pathways in mitigating uneven zinc deposition.

These findings highlight a promising and scalable strategy for developing high-performance, environmentally friendly anodes for AZABs. Future work will focus on mechanistic studies of dendrite suppression, electrolyte optimization, and the integration of this system into flexible or hybrid battery architectures.

References

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