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Research Progress and Prospect of Current Collector for Aqueous Zinc Ion Batteries

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Abstract

To address the bottlenecks of zinc anodes in aqueous zinc-ion batteries (AZIBs), including dendrite growth, hydrogen evolution reaction (HER), corrosion, and insufficient cycling stability, structural and interfacial design as well as functional modification of current collectors are critical for uniform Zn deposition and performance enhancement.This paper reviews the progress of AZIB current collectors classified by material systems, covering traditional metal (Cu, stainless steel, Al-based) and novel (carbon, MXene, MOFs) current collectors, and analyzes the mechanisms of crystal facet engineering, alloying, 3D structural reconstruction, and zincophilic modification.Key challenges remain: the performance-stability trade-off in 3D structures, unclear interfacial regulation mechanisms, poor industrial scalability, and insufficient engineering validation.Future directions are proposed in theoretical calculation, in-situ characterization, scalable fabrication, and pouch cell verification, providing guidance for the design and industrial application of high-performance AZIBs current collectors.

Keywords:*Aqueous zinc-ion batteries (AZIBs);Current collector Zinc anode*

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I. Introduction

While lithium-ion batteries are already widely commercialized in consumer electronics and electric vehicles, their high total cost of ownership and the inherent flammability of their organic electrolytes remain the two key bottlenecks restricting their adoption in grid-scale large-scale energy storage applications[1]. By contrast, aqueous zinc-ion batteries (AZIBs) have garnered widespread attention in grid-scale energy storage applications, owing to their key advantages of low cost, high intrinsic safety, and environmental benignity[2]. Central to these advantages, the zinc metal anode exhibits a high theoretical volumetric capacity of 5855 mAh $cm^{-3}$and gravimetric capacity of 820 mAh g^{-1}, as well as a favorable low redox potential of -0.762 V vs. standard hydrogen electrode(SHE), enabling high energy density within the stable electrochemical window of aqueous electrolytes[3]. Despite these promising characteristics, the practical commercial application of AZIBs remains limited by critical interfacial bottlenecks at the zinc metal anode, primarily including uncontrolled dendrite growth and severe interfacial hydrogen evolution reaction (HER). Specifically,dendritegrowthoriginates from spatially inhomogeneous Zn^{2+} deposition, while HER arises from the thermodynamic instability of H_2O molecules at the zinc anode/electrolyte interface[4]. These issues trigger a series of cascading adverse effects: the aforementioned interfacial side reactions drive continuous electrolyte consumption and interfacial instability, directly leading to rapid capacity fading and deterioration of Coulombic efficiency; meanwhile, uncontrolled dendrite growth can penetrate the separator and induce internal short circuits. Both effects ultimately degrade the cycling life and safety performance of the battery[5].

To address the aforementioned critical bottlenecks of zinc metal anodes, researchers have developed a range of viable strategies to optimize anode performance, which can be classified into four mainstream research directions:(1) Construction of artificial interphases on zinc metal anode surfaces[6, 7]: This strategy enables direct and targeted regulation of the deposition environment at the zinc anode–electrolyte interface. It not only provides a robust physical protective barrier for the zinc anode, but also introduces uniformly distributed active zinc nucleation sites, ultimately improving the electrochemical reversibility of zinc plating/stripping, suppressing dendrite growth and interfacial side reactions, and enhancing the long-term cycling stability of the battery.(2) Modification and optimization of electrolyte systems[8-10]: This strategy is mainly implemented by introducing functional electrolyte additives or constructing highly concentrated electrolyte (HCE) systems, to regulate the solvation sheath structure of Zn^{2+}, optimize Zn^{2+} transport kinetics, and raise the homogeneous nucleation overpotential of zinc to suppress stochastic heterogeneous nucleation. While enabling uniform zinc deposition, this strategy also effectively inhibits parasitic side reactions at the zinc anode–electrolyte interface, including hydrogen evolution and corrosion.(3) Structural design of alloyed anodes[11-13]: This strategy constructs Cu-Zn-based intermetallic alloy interlayers on zinc anode surfaces to enhance the adsorption strength toward zinc atoms, markedly improve the electrochemical stability and corrosion resistance of the anode interface, and thereby induce dendrite-free, uniform zinc deposition and boost the cycling reversibility of the battery.(4) Structural design and functional modification of current collectors[3, 14]: This strategy constructs zincophilic functional layers on the current collector surface or designs three-dimensional (3D) porous conductive frameworks, enabling targeted regulation of zinc growth behavior from the very onset of zinc nucleation. Unlike the other three strategies that only enable post-hoc mitigation of irregular zinc deposition, this approach targets the root cause of inhomogeneous Zn deposition, establishing it as a core technical strategy to suppress dendrite growth and enhance the long-term interfacial stability of Zn anodes. Among the four strategies outlined above, current collector engineering delivers the most fundamental control over zinc deposition behavior. The geometric morphology, surface chemistry, and electronic structure of the current collector directly govern zinc metal deposition behavior during repeated galvanostatic charge-discharge cycles. Therefore, rational structural design and surface and interface modification of current collectors can fundamentally mitigate the key challenge of inhomogeneous zinc deposition at the anode.

To address the critical bottlenecks of AZIBs -uncontrolled dendrite growth, hydrogen evolution reaction (HER)-driven corrosion, and poor cycling stability-structural design and functional modification of current collectors have emerged as a key breakthrough to optimize zinc anode performance. Beyond hosting active materials and conducting electrons, rationally designed current collectors can precisely regulate zinc nucleation, suppress parasitic side reactions, and improve battery safety and cycling life.Extensive studies on AZIBs current collectors have expanded matrix materials from conventional metals to emerging functional materials (carbon-based materials, MXene, MOFs), and modification strategies from basic surface coatings to multidimensional precision designs. However, the field still faces four core challenges: performance trade-offs in 3D design, unclear interfacial regulation mechanisms, lab-industry fabrication mismatch, and insufficient engineering validation, with few comprehensive systematic reviews available.Herein, this review elaborates on the research progress of AZIBs current collectors by matrix material, analyzes modification mechanisms and electrochemical performance, summarizes key bottlenecks, and outlines future directions, aiming to provide theoretical and practical guidance for the rational design and industrial application of high-performance AZIBs current collectors.

II. Result And Discussion

1.Classification of current collectors

Current collectors perform two core electrochemical functions: serving as the host for active materials and enabling efficient electron transport between the active materials and the external circuit. Building on these core functions, the rational design of current collectors can precisely regulate zinc deposition behavior and play a critical role in suppressing HER, dendrite growth, and zinc anode corrosion. Extensive literature has confirmed that rational design of the morphology, structure, and chemical composition of current collectors can effectively guide uniform zinc deposition, thereby inhibiting both the nucleation and subsequent growth of zinc dendrites[15]. Beyond their electrochemical functions, current collectors also enable effective thermal management: they facilitate heat dissipation to mitigate heat accumulation during cell operation, which directly improves the safety and cycling life of the full cell.Therefore, the screening and functional design of high-performance current collectors should satisfy a set of core performance criteria: high electronic conductivity, excellent chemical and electrochemical stability in aqueous electrolyte operating environments, favorable mechanical strength and structural stability, low mass density, low production cost, and industrial scalability. In the following sections, we systematically discuss the application of metal-based current collectors in AZIBs, grouped by their matrix material systems.

1.1 Copper-based current collectors

InAZIBs, copper-based materials (including copper foil, copper mesh, and 3D porous copper foam) have become one of the most widely adopted anode current collectors in AZIBs and other secondary ion battery systems, owing to their mature fabrication protocols, low cost for scalable industrial manufacturing, ultrahigh electronic conductivity, and intrinsic zincophilicity. Specifically, the ultrahigh electronic conductivity of copper-based materials effectively reduces the charge transfer impedance at the electrode interface, while the 3D structure of copper mesh and copper foam markedly increases the electrochemically active surface area of the electrode and homogenizes the interfacial current distribution. These synergistic effects guide uniform nucleation and deposition of Zn^{2+} on the current collector surface, suppress zinc dendrite nucleation and growth at their origin, and significantly enhance the cycling stability of the battery.Beyond these inherent advantages, surface modification of copper foil, copper mesh, and copper foam-including crystal facet engineering, alloying, and deposition of zincophilic functional coatings-can further optimize zinc deposition kinetics, suppress parasitic side reactions including HER and interfacial corrosion, and substantially enhance the Coulombic efficiency and long-term cycling life of the battery.Despite these performance benefits, commercial copper foil, copper mesh, and copper foam are inevitably plagued by intrinsic defects generated during industrial manufacturing, including surface scratches, pits, and heterogeneous surface roughness of the porous framework. These defect sites induce a pronounced tip effect, leading to spatially inhomogeneous deposition of Zn^{2+} during galvanostatic charge-discharge cycles. This inhomogeneous deposition further exacerbates dendrite growth and parasitic side reactions, and severely degrades the overall electrochemical performance of the battery.Despite the intrinsic zincophilicity of copper, spontaneous galvanic corrosion of zinc occurs on the surface of copper-based current collectors upon prolonged cycling and calendar aging. This phenomenon is particularly pronounced in zinc powder-based batteries, where porous zinc powder particles are loaded onto the copper foil surface, enabling electrolyte penetration into the active material/substrate interface and the formation of galvanic corrosion microcells reported in previous work[16].Therefore, when copper-based materials are employed as anode current collectors in AZIBs, surface modification strategies are still necessitated to mitigate the aforementioned limitations and further enhance the electrochemical performance of AZIBs.

1.1.1 Copper foil and surface modification

Copper foil is one of the most widely used current collectors forAZIBs, with excellent conductivity, chemical stability, mechanical flexibility, intrinsic zincophilicity, and high interfacial tunability.Xiao et al.[17] prepared single-crystal copper foil with fully exposed Cu facets via high-temperature annealing, elucidating the epitaxial matching between copper crystal facets and zinc deposition. The optimal Cu(111) facet enabled uniform, dendrite-free zinc deposition, with corresponding cells delivering 99.93% Coulombic efficiency, 880 stable cycles in symmetric cells, and 80% capacity retention after 811 cycles in anode-free MnO_2//Zn full cells.Tang et al.[18] fabricated a scalable Cu_6Sn_5@Cu composite current collector via facile electroless plating on large-area commercial copper foil. The Cu_6Sn_5 alloy layer regulates Zn^{2+} flux, reduces nucleation overpotential, and induces lateral zinc growth; it also undergoes spontaneous alloying to form zincophilic phases that buffer volume variation, elevate the hydrogen evolution overpotential, and suppress parasitic side reactions. The corresponding symmetric cell cycled stably for 7000 h at 50% depth of discharge, with the MnO_2//Zn full cell retaining 72.4% capacity after 2000 cycles.These works confirm that rational interfacial modification of copper foil can effectively solve core zinc anode bottlenecks, providing critical guidance for the design and industrial application of high-performance AZIBs current collectors.

Zhang et al.[19] fabricated a scalable CNO@Cu composite layer (carbon nano-onions embedded in copper matrix) on commercial copper foil via electrodeposition for AZIBs anode current collectors. The composite retains high intrinsic conductivity, while CNOs provide zincophilic sites to regulate Zn^{2+}flux, induce dendrite-free zinc deposition, and suppress parasitic side reactions. The corresponding cells delivered 99.89% average CE with 1400 stable cycles, 176 h cycling life at 85.5% DOD, and 194.8 Wh L^{-1} volumetric energy density in anode-free full cells, offering a cost-effective industrial AZIB solution.In a parallel study, Sun et al.[20] constructed a 3D copper nanowire network (AP-Cu) on commercial copper foil via ultrafast Joule heating welding. The high-curvature 3D network generates a uniform micro-electric field to regulate zinc nucleation, suppress tip effect-induced dendrite growth, and prevent dead zinc formation via a self-activation mechanism. The modified collector delivered 99.85% average CE with over 3000 stable cycles, and the corresponding full cell retained 135 mAh g^{-1} capacity after 1500 cycles. This roll-to-roll compatible process provides an industrially viable route for high-performance 3D copper foil modification.

1.1.2 Copper mesh and surface modification

Copper mesh current collectors represent a 3D-structured variant of planar copper foil. Their porous structure enables electric field homogenization and their lighter weight boosts full-cell energy density, making them widely studied inAZIBs.Zhang et al.[21] prepared an integrated current collector–zinc anode by laminating zinc foil with copper mesh (CM) via room-temperature cold pressing. The 3D copper network and its intrinsic zincophilicity act synergistically: DFT calculations show preferential Zn^{2+} adsorption on copper surfaces and in lattice gaps, while COMSOL simulations confirm uniform electric field and current distribution to eliminate the tip effect. The high surface free energy and good electrolyte wettability further promote uniform Zn^{2+} nucleation and deposition, suppressing dendrite growth and HER-related parasitic reactions.Symmetric cells based on this modified copper mesh exhibited long-term cycling stability: over 4000 h at 1 mA cm^{-2} and 2800 h at 5 mA cm^{-2}, respectively. Zn‖ Cu asymmetric cells achieved an average CE of 99.8% over 1000 cycles. The MnO_2-based full cell maintained 65.5% capacity after 500 cycles at 1 A g^{-1}. This work offers a simple, scalable route toward dendrite-free zinc anodes.

Liu et al.[22] modified a commercial copper mesh (CM) with Cu_2O nanoparticles via hydrothermal and annealing processes to construct a Cu_2O/CM composite current collector for aqueous zinc battery anodes. The 3D Cu mesh offers a stable substrate and mechanical support, while Cu_2O enhances specific surface area and wettability. During initial cycling, Cu_2O irreversibly transforms into metallic Cu, creating uniformly dispersed zincophilic sites. This design synergistically reduces local current density and nucleation overpotential, and homogenizes the electric field via its 3D structure, suppressing dendrites and hydrogen evolution. Symmetric cells achieved over 700 h at 1 mA cm^{-2} (1 mAh cm^{-2}) and 200 h at 10 mA cm^{-2}. Zn‖ Cu cells showed 99.25% Coulombic efficiency over 400 cycles. A full cell with MnO_2/CNTs cathode retained 192.9 mAh g^{-1} after 950 cycles at 1 A g^{-1}. This work provides a simple, efficient route for zincophilic modification of Cu meshes.

1.1.3 Copper foam and surface modification

Inspired by lithium/sodium metal anodes, three-dimensional zinc-based host materials as customized current collectors have attracted attention. Their intrinsic electric field homogenization promotes uniform current distribution, while the three-dimensional porous structure increases substrate specific surface area[23]. Moreover, three-dimensional current collectors can accommodate higher zinc loading without increasing the overall electrode thickness, thus effectively alleviating the volume expansion effect during cycling. As a typical sponge-like three-dimensional porous network, copper foam exhibits excellent electrical and thermal conductivity as well as a large specific surface area. It serves as an electrode scaffold, providing structural support and optimizing reaction kinetics through its three-dimensional structure, enhancing stability and cycling reliability.To modify zinc anodes, Camurcu et al.[24] fabricated an ultra-thin three-dimensional porous copper foam (CuF5, 38 38 μm) current collector via the dynamic hydrogen bubble template method. This foam exhibits high conductivity and open porous structure. Its ultra-large specific surface area (5.68 m^2/g) is over three times that of commercial copper foam (1.78 m^2/g), significantly reducing local current density and ensuring uniform electric field/electrolyte distribution. Its low zinc nucleation overpotential (89 mV) and dense interconnected macro/micro-pores guide uniform Zn deposition/stripping, suppressing dendrites and volume expansion.Symmetrical cells with this modified copper foam cycled stably for more than 1000 hours at 0.1 mA·cm^{-2}. This work presents a promising, scalable route for the application of low-cost, ultra-thin copper foam current collectors.

Li et al. [25] fabricated a Cu foam@Zn composite anode for zinc anode modification in aqueous zinc-ion batteries, via a one-step electrodeposition process to uniformly deposit a zinc layer on the surface of commercial copper foam. The three-dimensional interconnected porous structure of copper foam homogenizes the distribution of current density and electric field, fundamentally alleviating inhomogeneous zinc deposition and inhibiting dendrite formation. In addition, its excellent electrical conductivity and favorable corrosion resistance can accelerate electrochemical reaction kinetics, reduce voltage hysteresis, and mitigate self-discharge behavior in the electrolyte.Compared with composite anodes based on copper foil or nickel foam substrates, Cu foam@Zn exhibits superior electrochemical performance: symmetric batteries based on this composite anode demonstrate a voltage hysteresis of only approximately 0.04 V and significantly enhanced cycling stability relative to pure zinc foil; full cells paired with a β-MnO_2 cathode retain a specific capacity of 206.9 mAh g^{-1} after 500 cycles at a current density of 1 A g^{-1}, with stable Coulombic efficiency. This performance confirms faster electrochemical kinetics, more uniform zinc deposition, and excellent cycling stability.

2. Current collector based on stainless steel (SS)

Stainless steel (SS) has also been explored for use in aqueous zinc-ion batteries (AZIBs). With its excellent mechanical strength, corrosion resistance in aqueous electrolytes, and cost advantages, stainless steel is a promising candidate for zinc anode current collectors in AZIBs. Stainless steel-based current collectors can be categorized into two main types: stainless steel foil and stainless steel mesh. Currently, the application of stainless steel current collectors in aqueous zinc batteries has attracted considerable attention. Nevertheless, unmodified stainless steel surfaces suffer from inadequate zincophilicity and high interfacial contact resistance. These issues can lead to non-uniform zinc deposition, dendrite growth, and interfacial peeling during long-term cycling. To optimize the interfacial compatibility with the zinc layer and enhance the reversibility of zinc deposition, surface modification is typically required to tailor the interfacial properties, thereby harnessing the structural stability and application potential of stainless steel in aqueous systems.

Li et al. [26] developed a zinc anode (PC-Zn@SSM) via in-situ growth on stainless steel mesh for seawater-based energy storage. Using seawater electrolyte with PEG and CA additives, they induced a cross-linked zinc nanosheet array with excellent interfacial compatibility, mechanical tolerance, and adhesion. PEG regulates Zn^{2+} deposition orientation, while CA promotes desolvation—together enabling a self-regulating, dendrite-free mechanism: uniform zinc deposition during charging and preferential nanosheet dissolution during discharging. The anode achieves 30 mAh cm^{-2}at 50 mA cm^{-2}. A seawater-based zinc–air battery delivers 285 Wh m^{-2} and powers small electronics. This work offers a viable strategy for low-cost, scalable seawater-based zinc batteries.

Zhao et al. [27] modified zinc anodes by fabricating a Cu-Sn@SSM current collector via co-electrodeposition of a low-nucleation-barrier Cu-Sn alloy layer on stainless steel mesh. The 3D mesh structure disperses current density, while the Cu-Sn layer spontaneously forms Cu-Zn alloy and Sn, creating abundant zincphilic sites for uniform ion distribution and dense Zn deposition. DFT confirms lower Zn adsorption energy on $Cu_{41}Sn_{11}$(660) (-1.69 eV) vs.bare SSM (-1.27 eV), and contact angle decreases from 122.4 degrees to 56.92 degrees, indicating enhanced zincphilicity and wettability. Symmetric cells achieve stable cycling more than 1050 hours (10 mA cm^{-2}, 3 mAh cm^{-3}), asymmetric Zn//Cu cells maintain 99.4 percent Coulombic efficiency over 2000 cycles (10 mA cm^{-2}), and full cells with NVO cathode retain 162 mAh g^{-1}after 1000 cycles (2 A g^{-1}, 84% retention). This addresses uneven deposition and dendrite growth caused by poor zincphilicity of stainless steel.

3. Aluminum-based current collectors

Aluminum (Al) is abundant (~8% of the Earth's crust), low-density (2.7 g cm^{-3}), low-cost, and highly conductive, making it a promising candidate for zinc anode current collectors in aqueous zinc-ion batteries (AZIBs). It is widely used in two forms: aluminum foil and aluminum foam.Aluminum foil is lightweight and scalable, improving the gravimetric energy density of batteries. The 3D porous structure of aluminum foam ensures uniform current distribution and accommodates volume expansion.However, aluminum foil easily forms a native oxide layer and suffers from corrosion, while aluminum foam requires complex, high-cost fabrication. Thus, surface modification is essential to optimize their interfacial properties and stability for practical applications.

Zhu et al.[28] fabricated an Al–Nb composite current collector by depositing a niobium (Nb) coating on commercial Al foil via DC magnetron sputtering, and validated its bifunctional application as both cathode and anode current collector inAZIBs.A thin, dense Nb_2O_5 passivation layer spontaneously forms on the Nb coating, which suppresses corrosion of the Al substrate by aqueous electrolytes, alleviates the high interfacial impedance of pure Al foil, and maintains high electronic conductivity.Tekaligne et al.[29] developed two organic corrosion inhibitors, 5-formyl-8-hydroxyquinoline (FHQ) and 8-hydroxyquinoline (HQ), as electrolyte additives to protect Al current collectors, and established a Zn//LVPF system to evaluate their inhibition efficiency.FHQ adsorbs onto Al foil via Nand O heteroatoms to form a protective film, reducing the corrosion rate in 21 m LiTFSI electrolyte from 2.29×10^{-2}mmpy to 1.37×10^{-3}mmpy and suppressing pitting corrosion.When applied in Zn//LVPF full cells, FHQ enabled 96.82% capacity retention and 98.63% average CE after 60 cycles at 0.2 C, while significantly enhancing cycling stability and mitigating self-discharge.

4. Carbon-based current collectors

Carbon-based materials are widely studied as current collectors. Pristine forms such as carbon nanotubes, cloth, fibers, graphene, and graphite fibers offer high conductivity, large surface area, chemical stability, and tunable porosity. Extensive research has focused on their structural and functional optimization, and the resulting porous composites further boost battery performance [30].Li et al. [31] hydrothermally coated carbon cloth (CC) with an ultrathin $NH_4V_4O_{10}$ (NVO) layer (CC@NVO-16) for dendrite-free flexible Zn anodes. The open NVO structure provides abundant zinc-philic sites; Zn^{2+} initially intercalates to form $ZnNVO_x$, lowering nucleation overpotential and mitigating CC's hydrophobicity. This accelerates Zn^{2+}transport, guiding uniform deposition and suppressing dendrites. At 1 mA cm^{-2}, CC@NVO-16 shows only 34 mV overpotential and sustains exceed 280 cycles with 99.21% average Coulombic efficiency; even at 10 mA cm^{-2} it achieves exceed 450 cycles at 99.46%, far outperforming bare CC or thick NVO coatings. This offers an effective modification strategy for flexible aqueous Zn batteries.Jiang et al. [32] used oxygen plasma treatment to modify carbon cloth (PTCC) as a Zn host. The treatment introduces uniformly distributed C=O zinc-philic groups and reduces the cloth's hydrophobicity. DFT confirms stronger binding of Zn with C=O than with C–C or C–OH, lowering the nucleation barrier. At 1 mA cm^{-2}, PTCC's nucleation overpotential is only 97 mV (vs. 186 mV for pristine CC). Consequently, PTCC enables uniform nucleation, highly reversible plating/stripping, and dendrite suppression. Even at 60% depth of discharge, Zn@PTCC symmetric cells cycle stably for 480 h; at 0.5 mA cm^{-2} they exhibit 25 mV hysteresis and exceed 530 h stability, markedly better than Zn@CC cells.

5. Other materials as current collectors

MXene has emerged as a promising 2D material for energy storage due to its zinc affinity and high conductivity, enabling uniform Zn^{2+} deposition [33]. Zhou et al. [34] fabricated a MXene/graphene aerogel (MGA) as a 3D zincophilic scaffold, densely encapsulating Zn via one-step electrodeposition to form a stable MGA@Zn composite anode. The F-terminals on MXene form a ZnF_2-rich SEI in situ, lowering nucleation overpotential and suppressing dendrites, while the 3D structure mitigates hydrogen evolution and passivation. The MGA@Zn symmetric cell cycles exceed1000 h at 10 mA cm^{-2}, and asymmetric cells achieve 600 cycles with 99.67% CE. Foldable quasi-solid-state batteries retain exceed91% capacity after folding at 60% DOD, offering a new design strategy for flexible Zn anodes.MOFs are also used to stabilize Zn anodes via porous structures and uniform nucleation sites[30]. Wang et al. [35] first used annealed ZIF-8 (ZIF-8-500) as a Zn host, retaining its 3D porous structure. Its high HER overpotential suppresses side reactions and dead Zn formation. Even at 30 mA cm^{-2}, CE remains 99.8%. Zn@ZIF-8-500-based supercapacitors retain 72% after 20000 cycles, and Zn–I_2 full cells retain 97% after 1600 cycles-far outperforming bare Zn foil-paving a new path for low-cost, reversible aqueous Zn anodes.

III. Conclusion

Research on current collectors for aqueous zinc-ion batteries (AZIBs) has expanded from traditional metallic substrates such as copper and stainless steel to emerging functional material systems including carbon-based materials, MXene, and metal-organic frameworks (MOFs). Modification strategies have also evolved from basic surface treatments to multidimensional and refined designs involving crystallographic plane engineering, alloying, and three-dimensional structural reconstruction. These approaches have proven highly effective in regulating zinc deposition behavior, inhibiting dendrite growth, and mitigating interfacial side reactions. However, the field still confronts critical bottlenecks: the inherent trade-off dilemma in the design of three-dimensional porous structures, a lack of systematic theoretical understanding regarding interface regulation mechanisms, a disconnect between high-performance fabrication processes and industrial production, and insufficient engineering validation tailored to commercial application scenarios.

Future research should focus on four key directions: first, integrating multi-scale computational approaches such as density functional theory (DFT), molecular dynamics, and phase-field simulations to establish a high-throughput screening and performance prediction system for current collector materials, enabling rational and targeted design of both materials and structures; second, leveraging in-situ characterization techniques to elucidate the fundamental mechanisms by which current collector interfaces regulate zinc nucleation and growth, thereby establishing clear structure-property relationships; third, developing low-cost, continuous modification technologies compatible with commercial roll-to-roll production processes to achieve scalable and controllable fabrication of high-performance current collectors; and fourth, conducting long-term cycling stability and comprehensive safety performance validation under commercial operating conditions within pouch cell architectures.

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