

Fiber-Shaped Zinc-Based Batteries: Mechanisms, Process, and Wearable Applications

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The development of novel flexible batteries with high performance and enhanced safety is a critical step toward advancing wearable technology and enabling its large-scale application. Fiber-shaped batteries have gained significant attention due to their unique advantages, such as miniaturization and weavability, making them well suited for wearable applications. Fiber zinc-based batteries have emerged as a promising candidate, benefiting from zinc's natural abundance, low redox potential, high theoretical capacity, cost-effectiveness, and intrinsic safety. Despite significant progress, including the development of integrated device systems and self-powered energy textiles, fiber zinc-based batteries still encounter

several challenges. Reversibility issues, such as dendrite formation and electrolyte instability, remain critical concerns, particularly frequent mechanical deformations and diverse application environments. Additionally, the complex fabrication process hinders large-scale commercialization by increasing production costs, reducing consistency, and limiting scalability. This review first presents the working principles of fiber zinc-based batteries, followed by an analysis of their design strategies and research progress. It then discusses the integration of fiber zinc-based batteries with other electronic devices and points out key challenges and prospects, aiming to inspire more research for their widespread practical use.

1. Introduction

The growing demand for flexible and wearable electronics has significantly accelerated the research and development of compact and flexible batteries.^[1] There is an urgent need to advance flexible energy storage technologies that integrate portability, flexibility, stretchability, and enhanced safety.^[2–4] Fiber batteries have garnered significant attention due to their advantages, such as miniaturization, weavability, permeability, and integrability, making them ideal for wearable electronics.^[5–7] In the past decade, various types of fiber-shaped batteries have continually emerged in research and development, such as fiber-based lithium batteries, fiber sodium-based batteries, fiber zinc-based batteries (FZBs), and fiber supercapacitors.^[8–11] Among them, FZBs have emerged as a promising power source for wearable electronics, owing to the abundant zinc reserves, low redox potential (-0.76 V versus SHE), high theoretical capacity (820 mAh g^{-1}), and inherent safety.^[12–14] Over the past decade, significant progress has been made in FZBs (Figure 1a).

Despite significant progress, several challenges remain unresolved in the newly proposed battery systems. Given the continuous deformations and variable operating environments, it is essential to address challenges related to material selection and structural

design in FZBs, such as dendrite growth and electrolyte leakage.^[15–17] Additionally, the fabrication of FZBs is complex and involves several key aspects, including current collector design, electrode coating, and battery separator packaging. A major challenge in facilitating the commercial adoption of these batteries lies in achieving high performance while ensuring low production costs, high consistency, and scalability. With ongoing advancements in materials science and manufacturing technologies, significant breakthroughs have been made in the research of FZBs. Electrochemical stability can be significantly enhanced by incorporating novel conductive materials, optimizing electrolyte compositions, and engineering advanced electrode structures. Meanwhile, the adoption of advanced manufacturing technologies such as wet spinning is expected to improve the consistency and large-scale production capacity of FZBs. Therefore, the key progress achieved in this emerging research frontier must be summarized with the hope of enlightening future research directions.

In this review, we first introduce the typical FZBs with different working mechanisms. We then summarize and analyze design strategies, recent research advancements, and the integration with wearable electronic devices. Finally, the key challenges and future perspectives for FZBs are discussed. This review aims to summarize the basic knowledge of the promising devices as innovative paradigms and inspire more researchers to find ways to develop better FZBs, ultimately facilitating their widespread adoption in practical applications.

2. Working Principles of Fiber Zinc-Based Batteries

The working principle and structural design of FZBs are critical to their overall performance. Based on their working mechanisms, FZBs can be categorized into conversion-type

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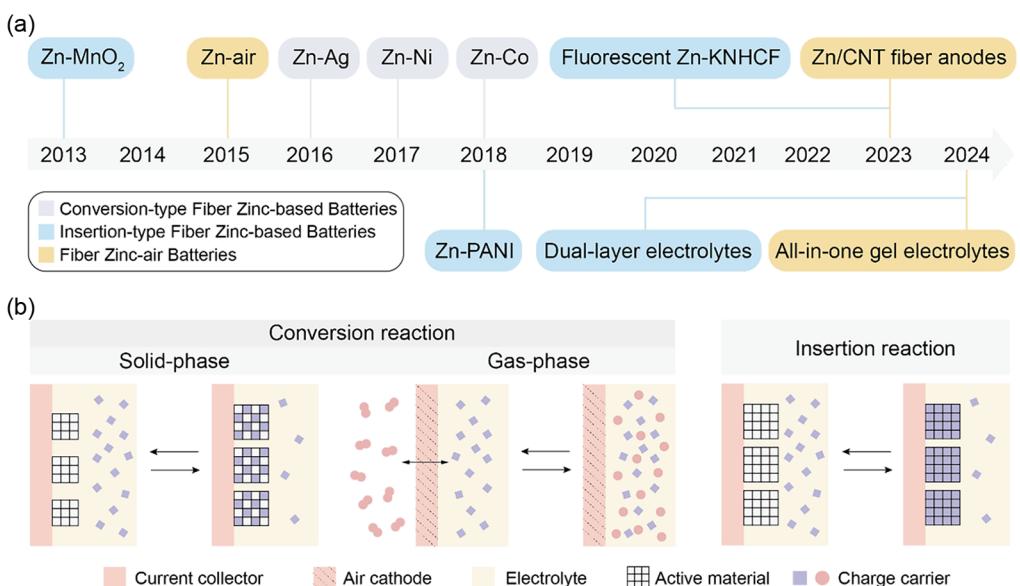
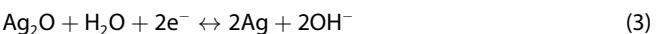


Figure 1. a) Brief development of FZBs. b) Schematic illustrations of different working mechanisms for FZBs.

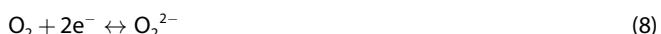
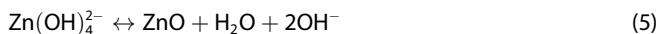
FZBs and insertion-type FZBs (Figure 1b).^[18–20] The construction of fiber-shaped zinc batteries requires synergistic engineering of three key components: the fiber anode, cathode, and electrolyte. Anode preparation typically involves the direct electrodeposition of zinc onto conductive fiber substrates or the direct use of zinc wires. For cathode fabrication, active materials are commonly deposited via dip coating, electrochemical deposition, or in situ growth onto fiber current collectors. However, the active materials of fiber zinc-air batteries come from the environment. Their air cathodes are usually prepared by dip coating or in situ growth of catalysts onto the carbon clothes and carbon nanosheets. Electrolytes are usually applied as gel systems for wearable applications. Gel electrolytes are prepared by dissolving polymer and salt components in deionized water and subsequently applied to the electrodes by drop casting or immersion. This section provides an overview of their distinct working principles.

2.1. Conversion-Type Fiber Zinc-Based Batteries

Conversion-type zinc-based batteries can be further divided into two types based on the reaction on cathodes: 1) solid-phase conversion-type FZBs and 2) fiber zinc-air batteries. During the solid-phase conversion reaction, the active materials in FZBs undergo a complete structural reorganization, resulting in significant crystal structure changes during charge and discharge (Figure 1b).^[21] Unlike conventional insertion/deinsertion mechanisms, this process does not require the host structure to remain intact. Instead, energy is stored and released through the formation and decomposition of new phases. Consequently, conversion-type active materials typically have simpler compositions and higher theoretical specific capacities. For example, redox pairs such as Ag₂O/Ag and NiOOH/Ni(OH)₂ exhibit high specific capacities in FZBs (Equation (1)–(3)),^[22] making them highly promising for flexible and wearable devices.



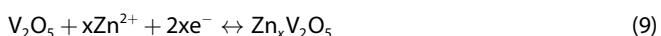
Fiber zinc-air batteries are gas-phase conversion-type zinc-based batteries which utilize oxygen as the cathode active material, offering a high theoretical energy density since oxygen from the air does not need to be stored (Figure 1b).^[23] Their operation relies on zinc oxidation at the anode and oxygen reduction at the cathode. The electrochemical behavior of fiber zinc-air batteries is strongly influenced by the electrolyte environment. Depending on the pH of the electrolytes, both the anode dissolution and cathodic oxygen reactions proceed via different pathways. Alkaline electrolytes are most frequently used for fiber zinc-air batteries. During discharge, zinc undergoes oxidation at the anode, releasing electrons to form Zn²⁺, while oxygen is reduced at the cathode in the presence of a catalyst, generating hydroxide ions (OH⁻). These OH⁻ ions then react with Zn²⁺ to form zinc hydroxide precipitates (Equation (5) and (6)). During charging, the reaction is reversed, decomposing zinc hydroxide and releasing oxygen (Equation (7)). Some neutral electrolytes such as Zn(OTf)₂ have been proposed for fiber zinc-air batteries. On the anode, zinc is reversibly oxidized to form Zn²⁺ (Equation (8)). On the cathode, a 2 e⁻ reaction pathway with higher reversibility than the conventional 4 e⁻ reaction pathway occurs (Equation (9)). Acidic electrolytes will lead to the corrosion of zinc and haven't been used in fiber zinc-air batteries. These mechanisms enable zinc-air batteries to achieve exceptionally high energy densities. However, the sluggish kinetics of the oxygen reduction reaction (ORR) and oxygen evolution reaction (OER) pose significant challenges, necessitating the development of cost-effective, efficient, and durable bifunctional catalysts.^[24]



Although conversion reactions offer higher capacities, materials relying on this mechanism often suffer from poor reversibility. The primary limitations include the following: 1) Significant phase transitions during charge/discharge cycles can lead to electrode pulverization, compromising structural stability. 2) The formation and decomposition of new phases are often accompanied by substantial volume changes, accelerating electrode degradation. 3) Certain conversion products may generate nonconductive byproducts that are difficult to reactivate, reducing Coulombic efficiency and cycle life. Therefore, enhancing the reversibility of conversion-type materials, mitigating structural degradation, and improving cycling stability remain key research challenges in this field.

2.2. Insertion-Type Fiber Zinc-Based Batteries

Embedded FZBs store charge through a reversible insertion and deinsertion mechanism of zinc ions (Figure 1b).^[25] The cathode material typically possesses a layered or tunnel-like structure, enabling the reversible intercalation and extraction of Zn^{2+} during charge and discharge. Various materials have been extensively explored as cathode candidates, including Prussian blue analogs, manganese oxides (Mn_xO_y), vanadium oxides (V_xO_y), and organic electrode materials.^[26] For instance, in V_2O_5 , Zn^{2+} intercalates into the V_2O_5 interlayers during discharge, forming $\text{Zn}_x\text{V}_2\text{O}_5$, and is subsequently extracted during charging, restoring the original V_2O_5 structure (Equation (4)). Unlike conversion-based batteries, insertion-type cathodes maintain their primary structure throughout the reaction, with only zinc ion migration occurring. This structural stability enhances reaction reversibility, improving electrode durability and extending the cycle life of flexible energy storage devices.



2.3. Preparation of Fiber Zinc-Based Batteries

The fabrication of FZBs differs significantly from that of their planar counterparts, requiring distinct strategies for preparing fiber anodes, cathodes, and electrolytes to meet their unique structural and functional demands.

Zinc wires or foils are commonly used directly as anodes in fiber-shaped zinc-based batteries. However, their limited mechanical properties and poor processability constrain further development in this field. Electrodepositing zinc onto conductive, flexible fiber substrates enhances battery flexibility and facilitates

integration into wearable textiles.^[14] Alternatively, wet spinning of fiber anodes composed of zinc powder and carbon nanotubes offers a scalable approach, significantly improving both production efficiency and structural uniformity.^[8]

The preparation of fiber cathodes generally follows a similar approach to that of fiber anodes. Certain metals, such as silver foil, can be directly employed as fiber cathodes in FZBs.^[21] Other cathode materials, such as MnO_2 and NiO , are typically fabricated via electrochemical deposition or *in situ* growth on fiber current collectors.^[22] In contrast, the cathodes in fiber-shaped zinc-air batteries differ fundamentally, as their active materials are derived from ambient oxygen. These cathodes do not store active material themselves but instead rely on catalysts to facilitate the reactions. Common fabrication methods include dip coating, spray coating, or *in situ* growth of catalysts on flexible carbon cloth or carbon nanosheets.^[23] In coaxial configurations of fiber zinc-air batteries, the air cathode is typically wrapped around the fiber substrate, ensuring efficient exposure to atmospheric oxygen while maintaining flexibility.

Electrolytes used in fiber-shaped batteries are generally classified as either liquid electrolytes or polymer gel electrolytes. Liquid electrolytes are typically prepared by dissolving salt components in deionized water and subsequently injected into encapsulated fiber batteries. In contrast, polymer gel electrolytes are more suitable for wearable applications due to their improved mechanical stability and leakage resistance. These gels are formed by dissolving or soaking polymers (e.g., PVA) in liquid electrolytes,^[9] followed by injection into the encapsulated fiber batteries or direct coating onto the electrode surfaces.

3. Process on Fiber Zinc-Based Batteries

3.1. Conversion-Type Fiber Zinc-Based Batteries

3.1.1. Solid-Phase Conversion-Type Fiber Zinc-Based Batteries

The advancement of flexible electronic devices necessitates fiber-based energy storage systems with enhanced characteristics such as high energy density, superior wearability, and structural adaptability. Recently, there has been a growing interest in conversion-type FZBs due to their multielectron transport in the conversion process, offering a significantly higher theoretical specific capacity and power output compared to intercalation-type systems. Solid-phase conversion-type FZBs hold great promise for flexible energy storage devices due to their exceptional safety and low costs. Aris et al.^[27] first proposed fiber Zn/Ag batteries, utilizing zinc-electroplated copper wires as the anodes and stainless-steel threads embedded with Ag nanoparticles as the cathodes (Figure 2a). The fabricated fiber Ag/Zn battery maintained over 98% capacity retention after 170 cycles with an energy density of 18.35 Wh kg^{-1} . To further enhance structural flexibility and stability, Aris et al.^[28] designed current collectors with helical spring configurations (Figure 2b). The prepared fiber Zn/Ag battery demonstrated exceptional durability, retaining stable electrochemical performance even after 17,000 bending cycles at a bending radius of 0.5 cm.

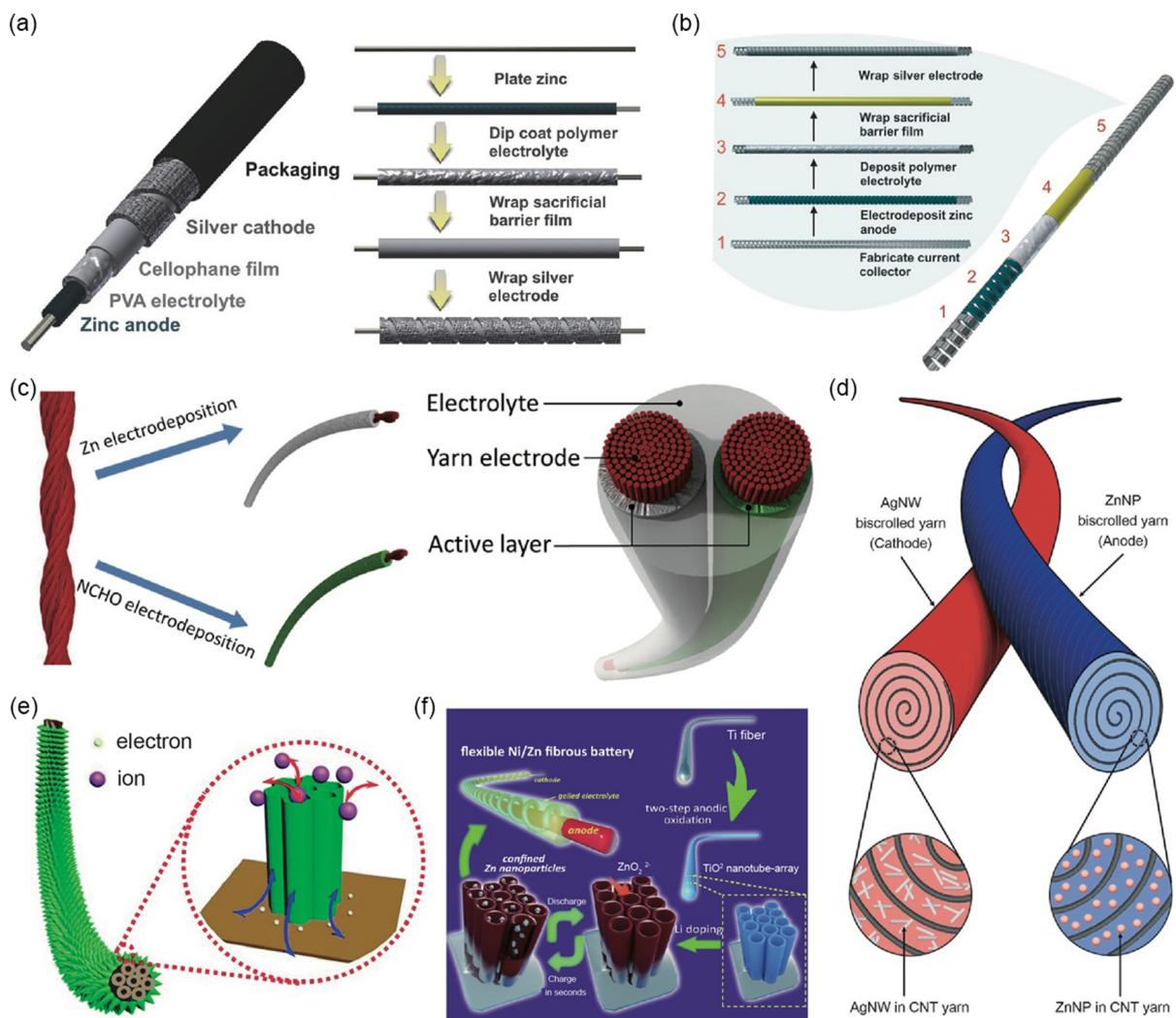


Figure 2. Conversion-type FZBs. a) Schematic illustration of the step-by-step assembly process of the fiber Zn/Ag battery. Reproduced with permission.^[27] Copyright 2016, John Wiley and Sons. b) Schematic illustration of the assembly process of the fiber Zn/Ag battery with helical spring configuration. Reproduced with permission.^[28] Copyright 2017, Ana Claudia Arias. c) Schematic illustration of the fiber NiCo/Zn battery based on conductive yarns electro-deposited with Zn and NCHO. Reproduced with permission.^[29] Copyright 2017, American Chemical Society. d) Schematic illustration of the Ag nanowire/CNT and Zn nanoparticle/CNT electrodes. Reproduced with permission.^[30] Copyright 2018, Springer Nature. e) Schematic illustration of the Ni-MOF-74@CNTF cathodes for fiber Zn/Ni batteries. Reproduced with permission.^[31] Copyright 2019, Royal Society of Chemistry. f) Schematic illustration of Zn anode and the construction of the fiber Zn/Ni battery. Reproduced with permission.^[32] Copyright 2018, Elsevier.

To enhance adaptability and fabric compatibility of collector structures in flexible batteries, researchers have acknowledged the pivotal role of collector flexibility in shaping overall flexibility and weavability. While structural approaches like coil springs mitigate rigidity constraints somewhat, the intrinsic brittleness of metal wire collectors often results in fractures during repeated bending, imposing more demanding criteria on the mechanical robustness of electrodes. The flexibility of current collectors plays a crucial role in determining the overall flexibility and weavability of the battery. However, the inherent rigidity of metal wire current collectors makes them prone to fracture under repeated bending, which imposes considerable mechanical strength requirements for yarn electrodes. Huang et al.^[29] developed a weavable fiber Zn/NiCo battery by electroplating zinc and nickel-cobalt hydroxide nanosheets onto highly conductive yarns (Figure 2c). The resulting fiber Zn/NiCo battery achieved an

energy density of 0.12 mWh cm^{-2} and exhibited an ultrahigh rate capability of up to 232C in the liquid electrolyte. Furthermore, Lee et al.^[30] embedded active materials within the yarns to increase the loading of silver and zinc to 99 wt%, achieving a capacity of $0.285 \text{ mAh cm}^{-2}$ in liquid electrolytes (Figure 2d). The optimization of collector structure alone has proven insufficient to comprehensively address the mechanical degradation and improve the overall electrochemical performance and cycling stability of FZBs for wearable applications. To achieve efficient and durable operation, a systematic research approach targeting the optimization of electrode materials is imperative.

Based on the initial progress in structural design, the electrochemical and structural properties of the cathode material itself have become one of the key factors determining the energy density and cycle life of FZBs. The ideal cathode should not only have the capability of high loading of active materials, but also have

excellent ion transport efficiency and mechanical flexibility to adapt to the complex and changing wearable application scenarios. Man et al.^[31] grew Ni-MOF-74 on carbon nanotube fibers (CNTFs) as a binder-free cathode (Ni-MOF-74@CNTF) for fiber Zn/Ni batteries (Figure 2e). Benefiting from its high specific surface area and well-defined 1D open-channel structure, the fiber Zn/Ni battery exhibited a maximum energy density of $186.28 \text{ mWh cm}^{-3}$ and a peak power density of 8.4 W cm^{-3} . Similarly, Zeng et al.^[32] designed a Ni-NiO heterojunction nanosheet cathode to construct a highly rechargeable fiber Zn/Ni-NiO battery. The improved conductivity and electrochemical activity of the Ni-NiO heterojunction nanosheets enabled the fiber Zn/Ni-NiO battery to achieve only 3.4% capacity decay after 10,000 cycles.

Despite advancements in high-performance cathode materials enhancing the energy output and cycling performance of FZBs, anode instability continues to limit overall battery efficiency. Under prolonged use and high-rate charge/discharge conditions, dendrite growth, uneven deposition, and interfacial corrosion of the zinc anode pose significant challenges to practical application. To tackle these issues, recent research has focused on innovative strategies in anode structural adjustment and interface engineering. Li et al.^[33] designed a lithium-doped 3D nanotube array-supported fiber anode (Li-RTiO_2), which enables zinc ions to deposit as nanoparticles within the nanotubes (Figure 2f). This strategy effectively suppresses dendrite formation and enhances the Zn/ZnO_2^{2-} reaction kinetics. The fabricated fiber Zn/Ni battery exhibited a volumetric energy density of 0.034 Wh cm^{-3} with only 5% capacity loss after 20,000 cycles. Mai et al.^[34] in situ grew $\text{ZnO}@C$ core-shell nanorods on carbon cloth as scaffolds for zinc deposition, forming a three-layered 3D CC-ZnO@C-Zn anode. Owing to the excellent dendrite suppression capability of the 3D scaffold, the assembled fiber Zn/Co battery achieved a volumetric energy density of 4.6 mWh cm^{-3} and retained 82% of its capacity after 1,600 cycles.

3.1.2. Fiber Zinc–Air Batteries

Zinc–air batteries utilize the abundant oxygen in the air as the active material, achieving a high theoretical energy density of 1086 Wh kg^{-1} , which makes it a highly promising energy storage solution for flexible and wearable devices.^[35] Peng et al.^[36] first proposed the concept of the flexible fiber zinc–air battery (Figure 3a). The proposed fiber zinc–air battery features an air cathode composed of aligned and cross-stacked CNT sheets, which act as the gas diffusion layer, catalyst layer, and current collector simultaneously. However, the multistep electron transfer processes of ORR and OER result in sluggish kinetics at air cathodes, posing significant challenges to both efficiency and longevity of fiber zinc–air batteries. Many efforts have been invested in finding proper electrocatalysts to reduce ORR overpotential and enhance battery discharge performance. To overcome this challenge, significant progress has been made in the development of bifunctional catalysts. Cobalt-based catalysts, owing to their multivalent nature, have emerged as highly promising candidates. Chen et al.^[37] utilized atomic layer Co_3O_4 nanosheets as

the bifunctional catalysts for OER and ORR (Figure 3b). Owing to the high catalytic activity of Co_3O_4 nanosheets, the fabricated fiber zinc–air battery exhibited stable discharge performance across a broad current density range of $0.4\text{--}4.8 \text{ mA cm}^{-2}$. Yu et al.^[38] reported a cobalt nanoisland catalyst (Co/Co–N–C) based on Co–N–C nanosheets. The synergistic effect between metal Co islands and Co–N–C nanosheets leads to outstanding bifunctional catalytic properties. This catalyst demonstrates a narrow charge–discharge voltage gap of 0.82 V at 10 mA cm^{-2} and a high power density of 132 mW cm^{-2} . Despite significant progress, current bifunctional catalysts are still facing the problems of insufficient activity and stability together with poor mass transport properties. Therefore, continuous efforts are needed to design and prepare highly efficient and robust bifunctional electrocatalysts and electrodes for electrically rechargeable zinc–air batteries.

Self-supporting electrodes in fiber zinc–air batteries play a crucial role in simplifying the battery architecture, enhancing the electrode mechanical stability, and facilitating efficient gas diffusion, which represents a promising avenue for boosting the energy density, extending the cycle life, and improving the overall practicality of fiber zinc–air batteries. Meng et al.^[39] proposed a 3D self-supporting bifunctional cathode composed of Co4N catalyst, carbon fiber network, and carbon cloth (Co4N/CNW/CC) (Figure 3c). Owing to its highly active catalytic sites, large specific surface area, and interconnected 3D structure, the Co4N/CNW/CC electrode demonstrates outstanding catalytic performance for OER and ORR. It exhibits a low OER overpotential of 310 mV at 10 mA cm^{-2} and an ORR half-wave potential of 0.8 V . Additionally, Zeng et al.^[40] fabricated a bifunctional electrode film by growing NiCo_2O_4 nanosheets on a nitrogen and oxygen dual-doped CNT film. This electrode film exhibits excellent catalytic activities for both OER and ORR with low Tafel slopes of 50 mV dec^{-1} for ORR and 92 mV dec^{-1} for OER.

Zinc wires are commonly used as the negative electrodes in fiber zinc–air batteries. However, conventional zinc wires suffer from structural instability during charge–discharge cycles, resulting in electrode degradation. Furthermore, their inherent high bending rigidity poses challenges for integration into flexible electronic devices. Integrating zinc powder into a flexible CNT substrate to form a composite fiber anode presents a promising solution (Figure 3d).^[41] Owing to its high electrochemical activity, and excellent flexibility, the resulting fiber zinc–air battery achieved a high specific capacity of 645.3 mAh g^{-1} and a maximum power density of 615.8 mW g^{-1} . Moreover, the mechanical flexibility of the hybrid Zn/CNT fiber anode ensures the stable electrochemical performance of the hybrid fiber anode-based ZABs even under complex deformation, highlighting their potential for practical applications in powering wearable electronics in the future.

The semi-open structure and large surface area of fiber zinc–air batteries severely limit the long-term stability of the devices and the feasibility of practical wearable applications. To enhance the operational reliability of fiber zinc–air batteries under multiple deformations and environments, the prevention of electrolyte evaporation remains a major challenge for stability. Zhang et al.^[42] utilized composite fibers soaked in KOH solution as electrolyte materials, leveraging their high water retention and

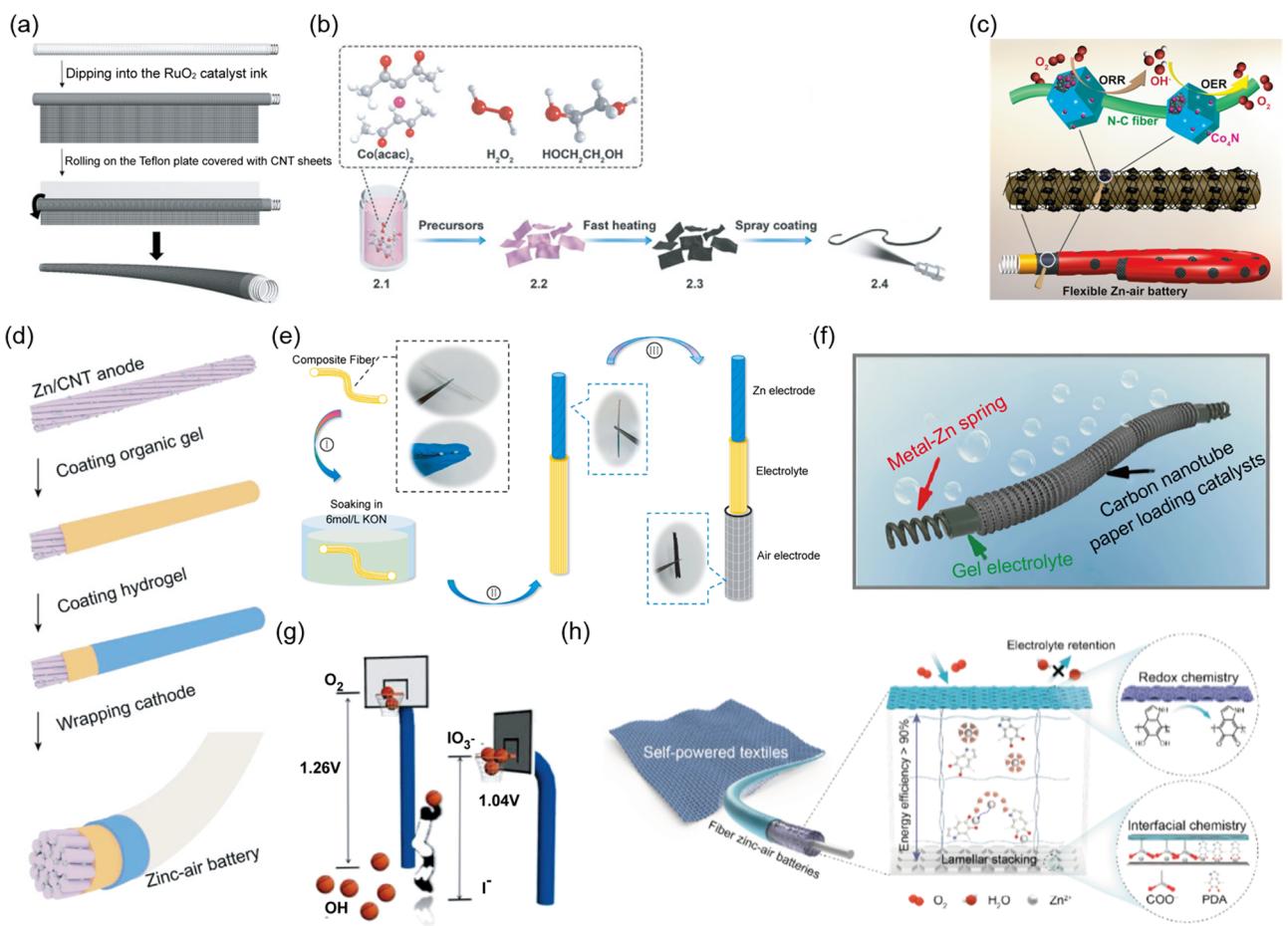


Figure 3. Fiber zinc-air batteries. a) Schematic diagram of the preparation process of a fiber zinc-air battery based on CNT films. Reproduced with permission.^[36] Copyright 2015, John Wiley and Sons. b) Schematic diagram of the preparation process of a fiber air cathode with Co₃O₄ nanosheets catalysts. Reproduced with permission.^[37] Copyright 2018, John Wiley and Sons. c) Schematic diagram of a fiber zinc-air battery with Co₃O₄/CNW/CC catalysts. Reproduced with permission.^[39] Copyright 2016, American Chemical Society. d) Schematic diagram of the preparation process of a fiber zinc-air battery based on the Zn/CNT anode. Reproduced with permission.^[41] Copyright 2023, John Wiley and Sons. e) Schematic diagram of the preparation process of a fiber zinc-air battery based on the composite fiber electrolyte.^[42] Copyright 2022, Elsevier. f) Schematic diagram of a stretchable fiber zinc-air battery based on the double network gel electrolyte. Reproduced with permission.^[43] Copyright 2019, John Wiley and Sons. g) Schematic diagram of I⁻/IO₃⁻ reaction modifier for regulating the charging process of a zinc-air battery. Reproduced with permission.^[44] Copyright 2019, John Wiley and Sons. h) Schematic diagram of a fiber zinc-air battery based on the all-in-one gel electrolyte. Reproduced with permission.^[46] Copyright 2024, John Wiley and Sons.

exceptional flexibility to ensure the stable operation of fiber zinc-air batteries under various deformation conditions (Figure 4e). Meanwhile, gel electrolytes have garnered significant attention due to their high ionic conductivity. However, conventional polymer gel electrolytes (e.g., PVA and gelatin) exhibit weak water absorption and poor interfacial interaction with electrodes, limiting their applicability in fiber zinc-air batteries. Ma et al.^[43] developed an alkaline-tolerant dual-network hydrogel electrolyte based on sodium polyacrylate (PANa) and cellulose (Figure 4f). This hydrogel electrolyte exhibits exceptional mechanical strength and high stretchability in strong alkaline solutions. As a result, the assembled fiber zinc-air battery could withstand a tensile strain of up to 500%. Future research should concentrate on designing molecular structures for high-performance gel electrolytes, constructing multifunctional synergistic interface layers, and developing comprehensive optimization strategies for electrolytes and electrodes at the device scale. These efforts aim to enhance the reliability of fiber zinc-air batteries in flexible smart fabrics.

In studies on enhancing the performance of FZBs, optimizing ion transport through rational electrolyte design, along with the incorporation of functional additives, has been shown to significantly improve energy conversion efficiency. Zhang et al.^[44] incorporated KI additives into the alkaline dual-network hydrogel electrolyte, effectively modifying the conventional reaction pathways and markedly improving the energy efficiency to 75% (Figure 3g). Similarly, Song et al.^[45] also developed an alkaline polymer gel electrolyte containing KI additives, which altered the traditional oxygen evolution reaction pathway and enabled a low charging voltage of 1.69 V. Furthermore, recent studies have demonstrated that optimizing electrolyte additives can simultaneously enhance the energy efficiency of the cathode and improve the stability of the zinc anode. Yang et al.^[46] proposed a polydopamine-based gel electrolyte as an all-in-one strategy for fiber zinc-air batteries (Figure 3h). By leveraging interfacial regulation and redox chemistry, the all-in-one polymer gel electrolytes significantly enhance zinc anode reversibility and

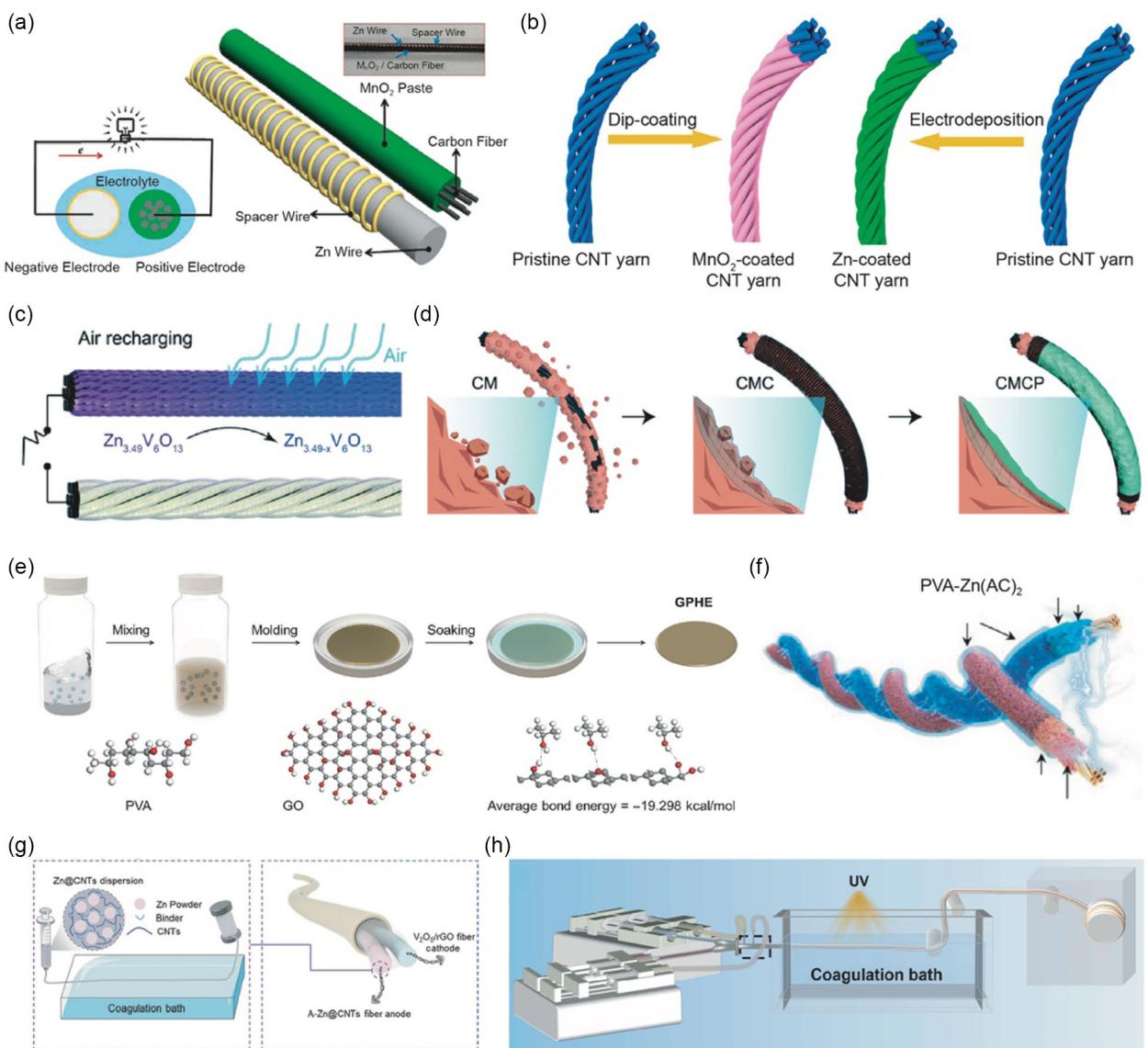


Figure 4. Insertion-type FZBs. a) Schematic illustration of the fiber zinc-ion battery based on Zn wire and MnO₂/carbon fiber. Reproduced with permission.^[47] Copyright 2013, Elsevier. b) Schematic diagram of the fabrication of the electrodes for fiber Zn/MnO₂ batteries. Reproduced with permission.^[17] Copyright 2018, American Chemical Society. c) Schematic of the fiber Zn/VCF battery during the air-recharging process. Reproduced with permission.^[49] Copyright 2021, Royal Society of Chemistry. d) Schematic illustration of the fiber MnO₂ cathode structure after sequential coating with CNT film and PEDOT films. Reproduced with permission.^[50] Copyright 2022, Royal Society of Chemistry. e) Schematic diagram of the preparation process of GPHE. Reproduced with permission.^[52] Copyright 2021, Jun Chen. f) Schematic diagram of the fiber ZnHCF/Zn battery based on a dual-layer gel electrolyte. Reproduced with permission.^[54] Copyright 2024, John Wiley and Sons. g) Schematic of A-Zn@CNTs fiber at different annealing temperatures. Reproduced with permission.^[55] Copyright 2024, John Wiley and Sons. h) Schematic diagram of the fabrication process of fiber zinc-ion batteries via coaxial wet spinning and in situ photopolymerization. Reproduced with permission.^[56] Copyright 2024, Elsevier.

accelerate the reaction kinetics of the air cathode, resulting in an impressive energy efficiency of 95% and a lifetime of 40 h.

Fiber zinc-air batteries have emerged as promising flexible energy storage devices due to their high theoretical energy density and intrinsic safety. Recent advancements have significantly improved their energy density, cycle life, and energy efficiency through the optimization of individual battery components. With ongoing advancements in material engineering and structural design, fiber zinc-air batteries hold great promise for applications in smart textiles, flexible electronics, and self-powered systems.

3.2. Insertion-Type Fiber Zinc-Based Batteries

The reversible ionic insertion mechanism, widely utilized in lithium-ion batteries, is also applicable to zinc-based batteries. A range of insertion materials, including manganese-based and vanadium-based compounds, Prussian blue analogs, and organic materials, have been extensively investigated as potential cathodes for insertion-type FZBs. Compared to conversion-type FZBs, insertion-type counterparts offer several advantages, such as enhanced safety, extended cycle life, and improved environmental compatibility, making them highly promising for wearable

energy storage applications. Yu et al.^[47] first proposed fiber Zn/MnO₂ batteries, utilizing zinc wires as the anodes and carbon fibers coated with MnO₂ slurry as the cathodes (Figure 4a). The resulting fiber Zn/MnO₂ battery achieved a discharge capacity of 158 mAh g⁻¹ at a current density of 70 mA g⁻¹.

An ideal fiber battery should possess excellent flexibility and mechanical strength, which can be further enhanced by replacing carbon fiber with other flexible and robust fibers as electrode substrates. Yi et al.^[48] utilized high-strength cellulose yarns as the electrode substrates, preparing the cathode via *in situ* polymerization of polyaniline (PANI) and the anode through electrochemical deposition of zinc. Owing to the mechanical support provided by the high-strength cellulose yarns, the fabricated fiber Zn/PANI battery operated effectively even under a mechanical load of 100 g. Li et al.^[16] fabricated fiber Zn/MnO₂ batteries using CNTFs as the current collectors of electrodes, achieving remarkable flexibility and stretchability of up to 300% strain (Figure 4b). Compared to metallic wires and carbon fibers, high-strength cellulose yarn has gained attention due to its lightweight nature, low cost, and sustainability. Further optimization of electrode material structures based on CNTFs can significantly enhance the capacity, durability, and electrochemical performance of fiber-based batteries. Liao et al.^[49] proposed an air-recharging fiber cathode composed of vertically aligned CNTs loaded with nanoscale V₆O₁₃ (Figure 4c). The nanostructured V₆O₁₃ undergoes spontaneous oxidation upon exposure to oxygen in the air, facilitating capacity recovery. The resulting fiber Zn/VCF (V₆O₁₃/CNT hybrid fiber) battery demonstrated a high specific capacity of 371 mAh g⁻¹ at a current density of 200 mA g⁻¹. Utilizing flexible, high-strength fibers like cellulose yarns and CNTFs as electrodes, combined with *in situ* active material construction and nanostructure regulation, enhances the structural stability of fiber batteries under deformation and significantly boosts their electrochemical performance. This approach establishes a foundation for developing truly wearable and reliable energy storage systems.

The stability and electrochemical activity of cathode-active materials play a crucial role in determining overall battery performance. During the charging and discharging process, cathode materials often detach due to volume expansion, mechanical stress accumulation, and weak adhesion between the electrode and current collector. These factors lead to capacity fading and reduced cycle life. To address this issue, Wang et al.^[50] wrapped MnO₂ fiber cathodes with CNT films to enhance mechanical integrity. Additionally, conductive PEDOT (poly (3,4-ethylenedioxithiophene)) was further introduced to fill microvoids between the CNT films and MnO₂, forming a robust hierarchical protective layer that further prevented active material loss (Figure 4d). As a result, the fabricated fiber Zn/MnO₂ battery exhibited a high specific capacity of 332 mAh g⁻¹ and maintained stable cycling for 4,000 cycles at a current density of 2 A g⁻¹. Defect engineering of cathode material offers an effective strategy to increase active sites, reduce ion migration barriers, and optimize electronic conductivity. Li et al.^[51] quenched V₂O₅ nanowires in NiCl₂ to modify the local electronic structure and vanadium coordination environment. This process improved charge transfer kinetics and provided additional storage and adsorption sites for Zn²⁺ ions. Consequently, the resulting fiber Zn/V₂O₅ battery demonstrated

excellent rate performance and achieved a volumetric energy density of 66.5 mWh cm⁻³.

Gel electrolytes play a crucial role in reducing leakage risks, suppressing zinc dendrite formation, and improving the mechanical flexibility of insertion-type FZBs. Xiao et al.^[52] incorporated graphene oxide (GO) into polyvinyl alcohol (PVA) to develop a hydrogel electrolyte with high ionic conductivity (21 mS cm⁻¹), excellent Young's modulus (530 kPa), and remarkable stretchability of ≈230% (Figure 4e). The resulting fiber Zn/MnO₂ battery retained 98.0% of its capacity after 1,000 cycles. Similarly, Wang et al.^[53] introduced ethylene glycol (EG) and GO into PVA to enhance zinc stripping-plating efficiency under extremely low temperatures. The fabricated fiber Zn/MnO₂ battery maintained a discharge capacity retention of over 22% even at -20 °C. However, the mismatch in elastic modulus between the electrodes and electrolytes leads to electrode-electrolyte interface separation, significantly impairing the electrochemical performance of insertion-type FZBs. To address these challenges, Li et al.^[54] proposed a dual-layer gel electrolyte strategy comprising a highly flowable polyvinyl alcohol-zinc acetate inner layer and a robust zinc alginate outer layer (Figure 4f). This dual-layer design significantly enhances interface stability, enabling the assembled fiber Zn/ZnHCF battery to retain 97.7% of its capacity after 500 bending cycles.

Currently, research is mainly aimed at enhancing the flexibility of FZIBs, with focusing on flexible substrates, which often neglect the electrochemical properties of fibrous Zn anodes under continuous deformation. Conventional rigid zinc wires exhibit limited mechanical flexibility and electrochemical stability, resulting in anode fracture under bending and dendrite formation during cycling. Consequently, the precise control of surface morphology and Zn crystalline texture on the anode becomes imperative to attain high mechanical flexibility while inhibiting the side reaction and dendrite formation. To overcome this limitation, Shao et al.^[55] employed wet-spinning technology to fabricate zinc powder-based fiber anodes, followed by annealing to induce the preferential orientation of the zinc (002) crystal plane (A-Zn@CNT) (Figure 4g). Owing to the excellent mechanoelectrochemical stability of A-Zn@CNT fiber anodes, the resulting fiber Zn/V₂O₅ battery exhibited remarkable cycling stability, operating steadily for 800 h at 1 and 1 mAh cm⁻². Additionally, it retained 88.6% of its capacity even after bending, knotting, and stretching deformations, highlighting its superior mechanical robustness and electrochemical stability. It has also been seamlessly woven into fabrics, thereby verifying its vast potential in powering smart textiles. This research provides valuable insights into the rapid advancement of smart textiles, particularly in the realm of flexible and long-life fibrous batteries for the next generation.

The continuous production of insertion-type FZBs is essential for improving efficiency, lowering manufacturing costs, and enabling large-scale applications in wearable electronics and smart textiles. To tackle challenges in continuous fabrication, two main strategies have been investigated: surface coating/deposition and the wet-spinning technique. The wet-spinning method, which integrates Zn powder into fibers using viscosity-enhancing additives such as polymers, allows for precise control

of Zn content and stabilizes the interface between Zn and conductive additives. Li et al.^[56] developed a coaxial wet-spinning process to fabricate stretchable fiber Zn/MnO₂ battery with a dual concentric sheath structure, significantly simplifying the fabrication process (Figure 4h). Similarly, Gao et al.^[57] employed continuous wet spinning with inks containing cellulose nanofibers (CNFs), carbon nanotubes, and active materials to produce fiber Zn/MnO₂ batteries. The fabricated fiber Zn/MnO₂ batteries demonstrated a high specific capacity of 281.5 mAh g⁻¹ at 0.25 A g⁻¹ and an ultrahigh energy density of 47.3 Wh kg⁻¹.

4. Applications of Fiber Zinc-Based Batteries

The rapid progress in flexible wearable electronics has spurred the development of more portable and lightweight energy storage devices. Although there is an essential difference in the electrochemical reaction mechanism between insertion-type and conversion-type FZBs, they have a certain functional overlap and complementary applications in the field of flexible wearables. FZBs are driving advancements in smart textiles and wearable electronics, offering exceptional flexibility, high energy density, and multifunctionality. By seamlessly integrating with functional modules such as sensing, display, fluorescence, and wireless communication, these batteries not only streamline system design and enhance wearability but also significantly improve device intelligence and functionality. Moreover, fiber-powered electronic textiles exhibit outstanding durability and environmental adaptability, presenting innovative solutions for applications in smart healthcare, sports monitoring, and flexible displays.

Wearable smart textiles provide an ideal platform for integrating multiple functional fibers to enable real-time sensing and response. However, the numerous interfaces between different fibers introduce complexity and compromise wearability. Advances in multifunctionality and integration have started to enrich the application scenarios of FZBs. For example, gas, pressure, and piezoresistive sensors have thus far been integrated with FZBs. Meanwhile, the development of wearable strain sensors that detect mechanical deformations provides a new opportunity for integration with FZBs, which will enable potential applications in healthcare monitoring, electronic skins, and human-machine interfaces. Zhang et al.^[58] reported a FZB integrated with a strain sensor composed of a carbon nanotube/polydimethylsiloxane (CNT/PDMS) film, exhibiting both high-performance energy storage and precise sensing capabilities (Figure 5a). Beyond sensing applications, FZBs can also be integrated with light-emitting displays, further expanding their potential uses. Liu et al.^[59] proposed a fluorescent fiber zinc-ion battery that incorporates fluorescent carbon dots with abundant zinc-affinitive groups as additives, achieving both zinc anode protection and fluorescence emission (Figure 5b). Benefiting from the unique 1D structure of fiber batteries, the fluorescent fiber zinc-ion battery maintains uniform luminance in all directions. Furthermore, it can be seamlessly integrated into smart textiles, offering an innovative solution that combines wearable display functionality with energy supply.

Aside from the advancement of multifunctional fiber batteries, FZBs can be seamlessly incorporated into various fiber devices to enable profound integration of energy storage and functional modules. The integration of FZBs with solar cells, three-phase generators, and biofuel cells has significantly contributed to the innovation of flexible energy harvesting and storage systems, addressing the constraint of the recharge and reuse of fiber batteries. Liao et al.^[49] integrated the fiber VCF/Zn battery and the strain sensor into a wearable fingertip (Figure 5c). When the finger repeatedly curves, the strain sensor fiber responds instantly, demonstrating the feasibility of this fiber battery for self-powering wearable systems. This study provides a new strategy to realize the self-powering functionality at the material level within simplified, flexible device configuration, contributing to the advancement of wearable electronic systems. Due to their stable voltage output, high power density, reliable safety, and strong flexibility, FZBs can be widely applied in intelligent electronic devices and wearable devices. Weaving FZBs into clothing to power wearable electronic products is the most common application. For example, Wang et al.^[50] braided fiber Zn-CMCP batteries into a flexible and breathable power strip to light an electronic watch, showing both decorative and energy-supply functions (Figure 5d). In addition, Shao et al.^[55] used the commercial braiding machine to weave FZBs into fabrics with an area of ≈200 cm² (Figure 5e), demonstrating its significant potential in powering smart textiles.

The integration of biomedical electronics with textiles has emerged as a prevalent trend in contemporary research. Conventional batteries, characterized by structural rigidity, limited lifespan, and substantial weight, are suboptimal power supplies for electronic textiles. In this context, FZBs offer a superior alternative. Integrating sensors, displays, and microchips into wearable textiles demonstrates the potential application of FZBs in various fields of the “Internet of Things” (IoT), including health monitoring and intelligent systems. Xiao et al.^[52] introduced the concept of a Textile Body Area Network (TBAN), a modular textile-based system powered by fiber Zn/MnO₂ batteries (Figure 5f). This system enables continuous monitoring of vital parameters such as pulse, temperature, humidity, and pressure, significantly broadening the application scope of wearable energy systems.

In the development of FZBs, both insertion-type and conversion-type systems face comparable technical challenges in practical applications. For example, electrode materials, when fabricated into fiber form, must maintain excellent flexibility, bending resistance, and weavability, while preserving their electrochemical performance. These requirements pose significant challenges to interfacial adhesion and the mechanical integrity of the materials. Moreover, once integrated into textiles, the battery components must exhibit long-term stability under environmental stressors such as perspiration, temperature fluctuations, and repeated washing—demanding durable performance from the electrode, electrolyte, and current collector. Regardless of the battery system employed, zinc anodes commonly suffer from issues such as dendrite formation, side reactions from water decomposition, and hydrogen evolution, all of which compromise cycle life and system safety.



Figure 5. Applications of FZBs. a) Demonstration of the preparation process for the multifunctional battery. Reproduced with permission.^[58] Copyright 2022, American Chemical Society. b) Schematic illustration and photographs of the fluorescent fiber zinc-ion battery. Reproduced with permission.^[59] Copyright 2023, American Chemical Society. c) Schematic diagram and photographs of the flexible finger sleeve with fiber VCF/Zn batteries powering the strain sensor. Reproduced with permission.^[49] Copyright 2021, Royal Society of Chemistry. d) Photograph of an electronic watch powered by three fiber Zn-CMCP batteries connected in series. Reproduced with permission.^[50] Copyright 2022, Royal Society of Chemistry. e) Schematic diagram and optical image of a fiber zinc-ion battery supplying energy to an LED strip in a wearable fiber fabric. Reproduced with permission.^[55] Copyright 2024, John Wiley and Sons. f) Schematic illustration of a fiber zinc-ion battery powering a multifunctional smart textile. Reproduced with permission.^[52] Copyright 2021, Jun Chen.

However, different zinc-based fiber batteries exhibit distinct material characteristics, electrochemical behaviors, and performance limitations, arising from their fundamentally different electrochemical reaction mechanisms. These intrinsic differences govern their suitability for specific application scenarios. Insertion-type FZBs utilize a positive electrode with a layered or tunnel structure that enables the reversible intercalation and deintercalation of Zn^{2+} . This mild reaction mechanism supports stable cycling and moderate energy density, making insertion-type systems ideal for applications requiring long-term operation, mechanical flexibility, and integration into wearable platforms, such as smart health monitoring textiles, and low-power sensing devices. In contrast, conversion-type FZBs rely on multielectron redox reactions between zinc ions and the cathode material, enabling higher energy density and faster power output. These characteristics make them suitable for high-demand, short-duration applications, including thermal garments and electrically responsive textiles. In the future, it is expected to explore the new approach that aims to combine the advantages of high energy density and extended cycle life, offering a

promising pathway for the development of high-performance, flexible fiber energy storage systems.

5. Summary and Outlook

In this review, the working mechanisms of FZBs are discussed. The design strategies and recent research advancements in FZBs are summarized. Finally, the applications for integration with other electronic devices are systematically analyzed. Although significant progress has been made in FZBs in recent years, many technical challenges remain to be addressed before widespread adoption is possible. The analysis is conducted from four perspectives: enhancing battery performance, standardizing evaluation criteria, scalable preparation, and developing wearable devices (Figure 6): 1) A key impediment to battery performance in FZBs lies in uncontrolled zinc dendrite formation and electrolyte degradation. To overcome this, advanced heterointerface engineering—such as constructing solid–electrolyte interphases with selective Zn^{2+} conduction—can direct uniform deposition

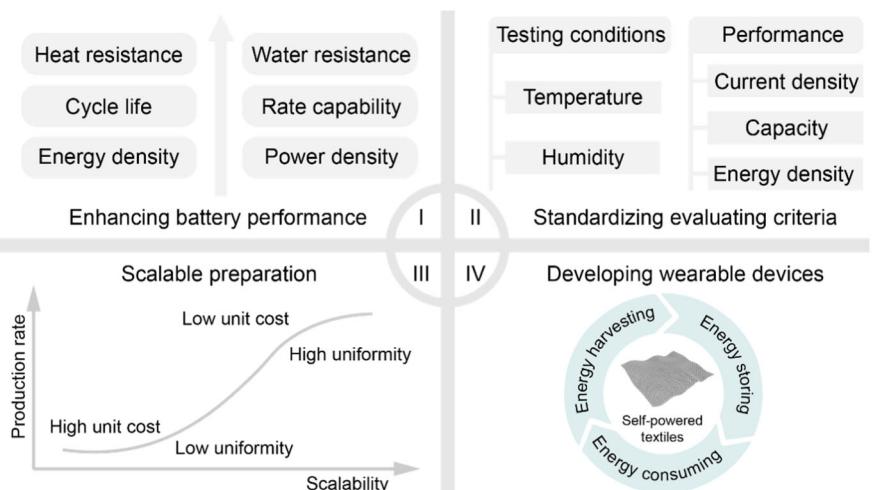


Figure 6. Future directions of FZBs.

and suppress parasitic reactions. Furthermore, the design of water-in-salt and solid-state electrolyte systems holds promise in enhancing interfacial stability and the deployment of operando analytical techniques is strongly encouraged to inform rational material design at the nanoscale. 2) Another pressing issue is the lack of standardized evaluation criteria. Currently, significant discrepancies exist in test conditions across studies, including variations in electrolyte composition, ambient temperature, and mechanical deformation states, making direct comparisons challenging. Moreover, inconsistencies in defining and calculating key performance metrics—such as specific capacity, current density, and energy efficiency—further hinder meaningful evaluation. Some studies derive these metrics solely from the electrode material, whereas others account for the entire device, making cross-study comparisons challenging. To overcome these challenges, it is crucial to establish a comprehensive multidimensional evaluation framework, which includes standardized definitions of device-level capacity, deformation-resilience tests under realistic conditions, and fatigue-resistance assessments. In addition, establishing a community-driven open-source benchmark database can facilitate reproducibility and foster collaborative progress. 3) Furthermore, the fabrication of FZBs remains confined to the laboratory stage, posing significant challenges for large-scale production. While conventional coating and electroplating techniques demonstrate promising results under laboratory conditions, they exhibit low efficiency in industrial applications and struggle to ensure uniform material deposition on fiber surfaces. Additionally, most existing manufacturing equipment is designed for planar batteries, making it unsuitable for fiber-shaped electrodes. To enable large-scale production, future research should focus on developing continuous manufacturing techniques tailored to fiber structures, such as automated methods based on spraying and 3D printing. Coupled with machine learning algorithms to optimize fabrication parameters, these methods would not only enhance fabrication efficiency but also improve the uniformity and controllability of FZBs. 4) In practical applications, FZBs must be further optimized to meet the specific requirements of wearable devices, including high safety, exceptional flexibility, and lightweight design. Moreover,

wearable electronics demand seamless integration between batteries and other components, such as sensors and communication modules, placing higher demands on structural design. Future research should focus on incorporating solid-state or organohydrogel electrolytes with self-healing and thermal resistance properties to enhance device resilience. Furthermore, codesigning FZBs alongside sensing and communication units on flexible substrates may lead to fully integrated, multifunctional electronics. Exploration of adaptive encapsulation materials will also be pivotal in improving durability under dynamic operating conditions.

As a promising energy storage technology that combines high energy density with structural flexibility, FZBs hold significant potential for wearable electronics. However, numerous challenges remain in both fundamental research and practical implementation. It is hoped that this review will stimulate further research and guide future developments in the field. With continued advancements, FZBs are expected to move closer to commercial viability, ultimately contributing to the evolution of human lifestyles.

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Conflict of Interest

The authors declare no conflict of interest.

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