The prosperity in portable and wearable electronics has stimulated researchers to develop safe, environmentally friendly, and efficient energy-storage technologies. Increased efforts have recently been made to fabricate high-performance rechargeable aqueous alkaline batteries (RAABs) as the frontrunner to complement and even replace the dominant lithium-ion batteries for large-scale energy storage due to the limited lithium resources and the use of flammable and toxic organic electrolyte. Compared with the conventional planar RAABs, fiber-shaped RAABs (FRAABs) manifest several intriguing features, such as miniaturization, adaptability, and weavability, making them an attractive candidate to power wearable and portable electronics. Herein, an overview of the recent progress in FRAABs by categories of fiber-shaped aqueous rechargeable Zn-based batteries, Fe–Ni batteries, and Bi–Ni batteries, with respect to the active electrode materials, device configurations, and battery properties, is comprehensively presented. Finally, the remaining challenges and possible solutions are emphasized as a useful guide for the further development of FRAABs.

1. Introduction
The rapid development of portable and wearable electronic products has brought great convenience to our lives, which has stimulated the increasing demand for flexible energy-storage devices.[1–3] Lithium-ion batteries (LIBs) is one of the optimum options due to their excellent electrochemical performance. However, the high cost and latent security issues largely hamper their further applications. In addition, the adoption of toxic and flammable organic electrolytes has pushed the community to explore other batteries with high safety and cost-effectiveness.[4–8] Compared with nonaqueous electrolytes (≈10 mS cm⁻¹), aqueous electrolytes with higher ionic conductivity (≈1 S cm⁻¹) are regarded as promising alternatives to organic electrolytes. Thus, rechargeable aqueous alkaline batteries (RAABs) have become an emerging energy-storage solution due to the use of aqueous electrolytes with high ionic conductivity, good
safety, and low cost, together with the simplified manufacturing conditions. Although the energy density of LIBs is higher than that of RAABs, the latter is more feasible for a wider range of practical applications, taking into account the overall performance, including safety, cycle life, and cost.  

Flexible RAABs with planar sandwich architectures have been first achieved, which consist of functional elements (e.g., nanoscale electrode materials, gel polymer electrolytes, highly flexible current collection elements, etc.) with bulky structures and limited flexibility, making them unsuitable for lightweight, miniaturization, and integration of wearable devices. Compared with flexible planar RAABs, fiber-shaped RAABs (FRAABs) are attracting tremendous attention due to the potential to miniaturize and the properties of high flexibility, superior deforming adaptability, and more importantly, the inherent compatibility with the textile industry, which provides a new way to power wearable and portable electronic devices.

In this Review, we present a comprehensive overview of the progress of FRAABs, specifically focusing on fiber electrode preparations, battery designs, and the electrochemical and mechanical properties. We aim to benchmark what exists, identify current issues, and predict what the future holds. First, the design principles of FRAABs with fiber electrodes, electrolytes, and device configurations are briefly introduced. Subsequently, the development of FRAABs such as Zn–Mn, Zn–Ag, Zn–air, Zn–Ni/Co, Ni–Fe, and Ni–Bi batteries are systematically summarized, emphasizing the fiber electrode preparations, device configurations, electrochemical mechanisms, and battery properties. Finally, we provide some valuable insights for the practical applications of FRAABs by discussing the existing challenges and future directions of FRAABs. Thus, this Review provides a worthy summary as a guide for developing FRAABs from laboratory research to practical applications.

2. Timeline of the Development and Design Principles of FRAABs

As shown in Figure 1, the developmental process of FRAABs and their multifunctionality are summarized with a brief timeline of their evolution. The fabrication process of FRAABs is more complicated than that of flexible planar devices. Fiber electrodes, electrolyte, and diaphragm (if required) are the basic components of FRAABs, as well as other functional components that are required to be compatible with the flexible fiber-shaped structure of the battery. At the same time, the manufactured FRAABs are supposed to possess the ability to accommodate varying repetitive deformations (e.g., bending, twisting, and stretching) with no significant degradation of their electrochemical properties, mechanical stabilities, and design functionalities. In addition, avoiding short circuits during long-term operation and repetitive deformation is essential. Therefore, the overall high performance of FRAABs depends on the utilization efficiency of the individual components and the configuration of the efficient devices. Except FRAABs, other fiber batteries have also been explored, as shown in Figure S1, Supporting Information. Back in 2012, the fiber LIBs were reported with Li wire as anode, which was then optimized with the use of aligned carbon nanotube (CNT) composite fibers. Subsequently, Li–S batteries with fiber shapes were also demonstrated in 2015. In the past few years, there has been a trend in transforming conventional planar-structured batteries into fiber shapes, to expand the application fields to wearable and biomedical scenarios. Fiber-shaped Li–air/CO₂, sodium-ion, zinc-ion, and NH₄-ion batteries have been successfully fabricated. The diverse battery systems operate based on different mechanisms and are thus endowed with respective advantages.

![Figure 1. Timeline of the development of FRAABs and their multifunctionality. Reproduced with permission.](image-url)
2.1. Fiber Electrodes

As a key component for achieving high-performance FRAAB, fiber electrodes are typically composed of two parts: the collector used for the electron/charge transport and the support matrix where the active materials/elements are located. Hence, in addition to being adaptable to various deformations, it is expected that they possess relatively good electrical conductivity and mechanical stability. For this reason, high conductivity and mechanical flexibility are the two major parameters to be considered when selecting fiber electrodes. Furthermore, consideration should be given to interfacial adhesion, mass density, specific surface area, and production cost. Typically, metallic wires offering exceptional electrical conductivity prove to be equally heavy and stiff, whereas the conductivity of lightweight polymer fibers with good flexibility is poor. In contrast, carbon-based fibers/nanofibers (e.g., CNT fibers and graphene fibers) offer broad prospects to serve as collectors in FRAABs due to their good electrical conductivity and relatively low mass density. Moreover, they also deliver high tensile strength, electrical conductivity, and large specific surface area.

2.2. Electrolytes

With regard to energy-storage applications, electrolyte is another crucial component of FRAABs, which governs the stable potential window, together with ion migration in the event of an electrochemical reaction. Although the operating potential of the aqueous electrolytes is typically restricted by the inherent characterized voltage of the hydrolysis (1.23 V), they have their own strengths and uniqueness, including ease of fabrication, safe operation, and low cost. Direct filling of liquid electrolytes along the fiber electrodes is complicated in the fabrication of FRAABs, and the problems of leakage and short circuit become more prevalent as these battery fibers are subjected to various distortions. In such cases, it is highly desirable to have mechanically robust and flexible partitions permeated with liquid electrolyte as well as efficient encapsulation. In addition, utilizing a gel polymer matrix as a mechanical backbone combined with an ionically conductive additive is the dominant strategy for satisfying the electrolyte requirements of FRAABs. As a result, these gel electrolytes enable good mechanical flexibility and stability. Therefore, they can facilitate the coating and sealing procedures to assemble the device with reduced size.

2.3. Device Configuration

The configuration of the device plays a crucial role and can greatly affect the electrochemical performance. In general, there are three types of basic FRAAB configurations, namely, parallel, twisted, and coaxial structures, as shown in Figure 2.[35]

2.3.1. Parallel Structure

Parallel structure is made by fixing two parallel fibrous electrodes on a flexible planar substrate, on which a gel electrolyte is applied. Despite having the simplest structure, parallel-structured FRAABs require external substrates to hold the devices together. Meanwhile, introduction of the flexible planar substrate results in compact FRAABs that are difficult to be woven in a flexible fabric and not suitable for high-volume integration.

2.3.2. Twisted Structure

Twisted structure is assembled by first soaking a pair of fibrous electrodes in gel electrolyte and then twisting them using a stepper motor after solidification of gel electrolyte on the surface of the fibrous electrodes. Such twisted structures show a similar structure as that of textile filaments. Thus, twisted FRAABs seem to be well suited for wearable applications and allow easy weaving into scalable energetic textiles. However, the fibrous electrodes of

![Figure 2](https://www.advancedsciencenews.com/fig/2020/02/2100060_2100060_003.jpg)

**Figure 2.** The schematics and comparisons of three different device configurations for FRAABs. Reproduced with permission.[35] Copyright 2020, Wiley-VCH.
the twisted structure can be easily separated during severe bending, which will lead to the disintegration of the whole device.

2.3.3. Coaxial Structure

The coaxial FRAAB exhibits a multiple-layer configuration in which a polymer gel is sandwiched between the core fiber electrode and the external electrode. The coaxial structure has a higher volume utilization than the twisted and parallel structures and accordingly can exhibit superior electrochemical performance. More importantly, the two electrodes of coaxial structures are in close contact with the electrolyte, maintaining the structural integrity. As a result, the coaxial structure can be well adapted to the bending process of practical applications. However, it remains challenging to accurately control the assembly process of FRAABs over such small fiber diameters, which is accompanied by restricted flexibility and therefore severely constrains the scalability of fabrication.

3. Recent Advances in FRAABs

RAABs, which use alkaline solution as electrolytes, undergo H\(^+\) insertion/extraction or conversion reaction processes.\[^{36}\] FRAABs have been considered to be promising energy-storage sources for wearable and portable devices due to their merits of inherent safety and low cost. Full cells with high voltage can be achieved through rational design by combining two battery materials with different potential windows in alkaline electrolyte. There are many kinds of FRAABs that can be manufactured by matching different fiber-shaped anodes and cathodes.

3.1. Zn—Mn Batteries

Due to the advantages of abundant resource and cost-effectiveness, MnO\(_2\) has been extensively implemented as cathode for Zn-based batteries. When using Zn-based anode for RAABs, the mechanism is normally based on the phase change between Zn and Zn hydroxides. In Zn—Mn batteries, the cathode is normally based on a reversible change between MnO\(_2\) and MnOOH (or even Mn(OH)\(_2\)). Yu et al. proposed adopting carbon fiber as the current collector and use the dip-coating method to fabricate the Zn—Mn battery (Figure 3a).\[^{37}\] Scanning electron microscopy (SEM) images proved the successful coating of MnO\(_2\) on the surface of carbon fibers, with varied electrode diameters upon different coating times (Figure 3b,c). The discharging capacity of the electrode slightly declined with the increased loading mass of MnO\(_2\), which might be ascribed to the higher resistance to electron transport arising from the growing thickness of the MnO\(_2\) paste (Figure 3d). In addition, the prepared battery exhibited mechanical stability upon repeated bending as well as consistent capacity with the increased length of batteries, enabling large-scale fibrous batteries’ manufacturing without compromise in performance (Figure 3e). Improving the electrochemical performance of MnO\(_2\)-based cathode has been attempted through different methods. MnO\(_2\) was coated with PEDOT through electrochemical deposition, which, as a buffer layer, can slightly improve the capacity of MnO\(_2\) cathode and greatly enhance the cycling stability when paired with Zn nanosheet anode.\[^{38}\] Nitridation of MnO\(_2\) was realized through thermal treatment with NH\(_3\).\[^{39}\] N doping in MnO\(_2\) can improve the electrical conductivity and alleviate the dissolution of Mn species, thus improving the capacity and cycling stability of the MnO\(_2\).
cathode in Zn–MnO₂ battery. Although these examples are not FRAABs, the concepts to improve the electrochemical performance of MnO₂ cathode can be adopted in Zn–Mn FRAABs. In addition to CNT fibers as the substrate to construct fiber Zn–MnO₂ batteries, photorechargeable fabrics have also been demonstrated by integrating with photovoltaic devices.

3.2. Zn–Ag Batteries

Zinc–silver batteries with high energy density, consistent discharge voltage, as well as environmental friendliness are the most prosperous aqueous batteries. Apart from having a specific energy density equivalent to that of commercial LIBs, Zn–Ag batteries are also endowed with safety and ease of mass production. Consequently, fibrous Zn–Ag batteries can be used as effective energy supply for various portable and wearable devices. In Zn–Ag batteries, the Ag cathode will be transformed into Ag₂O upon charging and reduced to Ag after discharging. Through embedding the silver nanoparticle ink into the conductive wire as the cathode and zinc plate as the anode, Alla et al. succeeded in constructing high-performance Zn–Ag batteries. The detailed fabrication process is shown in Figure 4a.[41]

Through optimizing the concentration of aqueous electrolyte to hinder silver ions’ dissolution and incorporating a cellophane film between the cathode and anode to inhibit the silver ions’ migration to zinc electrode, the battery life can be greatly increased. It was observed that dendritic Zn was deposited on the surface of copper wire, which can help maintain its mechanical integrity, whereas the compact ones were easy to fracture at higher current density (Figure 4b). The batteries delivered high discharging capacity of 1.4 mA cm⁻² at 0.5 C discharging rate as well as capacity retention of 98% after 170 cycles (Figure 4c). To gain higher flexibility and stretchability, Arias et al. proposed using the mechanically robust collector with specific geometries (serpentine or spiral springs) as structural substrate for battery assembly.[25] They manufactured the spiral-strip battery using the cold-roll method to compress the cylindrical copper wire into the strip, generating required dimensions and increasing the yield point of the material, as shown in Figure 4d. The cross-section SEM image presented the coaxial structure of the assembled batteries with Zn as the anode and Ag as the cathode and polyvinyl alcohol (PVA) as the gel electrolyte (Figure 4e). The battery delivered high discharge capacity of 1.25 mA cm⁻² at 0.5 C discharge rate and retained 94% of original capacity over 100 cycles (Figure 4f). Moreover, the spring-

![Figure 4.](image-url)

- (a) Diagram of preparation process of Zn–Ag battery.
- (b) SEM image of Zn with mechanical deformation.
- (c) GCD curves of the battery at 25% KOH. Reproduced with permission.[41]
- (d) The schematic manufacturing process of the spiral-structured Zn–Ag battery.
- (e) SEM image of cross section of battery.
- (f) GCD curves of battery at different cycles. Reproduced with permission.[25]
- (g) Diagram of fabricating process of Ag₂O electrode and assembled battery.
- (h) SEM image of Ag₂O@PEDOT:PSS.
- (i) GCD curves of the Zn–Ag₂O battery at various current densities. Reproduced with permission.[42]

Figure 4. a) Diagram of preparation process of Zn–Ag battery. b) SEM image of Zn with mechanical deformation. c) GCD curves of the battery at 25% KOH. Reproduced with permission.[41] Copyright 2016, Wiley-VCH. d) The schematic manufacturing process of the spring-structured Zn–Ag battery. e) SEM image of cross section of battery. f) GCD curves of battery at different cycles. Reproduced with permission.[25] Copyright 2017, AAAS. g) Diagram of fabricating process of Ag₂O electrode and assembled battery. h) SEM image of Ag₂O@PEDOT:PSS. i) GCD curves of the Zn–Ag₂O battery at various current densities. Reproduced with permission.[42] Copyright 2019, Royal Society of Chemistry.
shaped battery can endure more than 17,000 times bending, showing the superb potential for wearable electronics applications. The main bottlenecks in the widespread applications of Zn–Ag batteries are the poor cycling performance and low energy density, mainly attributed to structural crushing, Ag-ion migration, and limited loading of active materials. Li et al. took advantage of the metal–organic framework (MOF) skeleton as the current collector, which not only provides a larger specific surface area for the active materials and shortens ion/electron path, but also maintains the architectural integrity by reducing the stress involved in long-term electrochemical reactions. Figure 4g shows the detailed preparation process of the cathode, where the PEDOT:PSS acted as the protection layer to inhibit structural disruption and simultaneously alleviate silver-ion migration. It is notable that the Ag$_2$O nanoparticles were densely and smoothly distributed on the surface of the protection layer, as shown in Figure 4h. The as-assembled Zn–Ag$_2$O batteries provided high capacity of 1.05 mAh cm$^{-2}$ and high coulombic efficiency as well as nearly 80% retention rate over 200 cycles.

### 3.3. Zn–Air Batteries

Being intrinsically safe, environmentally friendly, and having high theoretical specific energy density (1086 Wh kg$^{-1}$, 3–4 times higher than current LIBs), aqueous rechargeable Zn–air batteries can be particularly suitable for portable energy-storage devices and wearable electronics. The air cathode normally involves reversible oxygen evolution/reduction reactions, using different electrocatalysts. Fiber-shaped aqueous rechargeable Zn–air batteries offer impressive electrochemical performance, light weight, compact size, and extraordinary wearability. An all-solid-state-cabled flexible Zn–air battery was manufactured by a screw-shaped Zn anode with a separate gel polymer and an air electrode with a nonprecious metallic catalyst, which avoids the drawbacks of Pt for being costly, less stable, and poor in kinetics. The fabrication process of the cable-shaped battery is schematically shown in Figure 5a. Cross-sectional optical microscopy observation of the cable-shaped flexible Zn–air battery is shown in Figure 5b, where the notable four-layered structure is clearly displayed. The comparative discharge curves

**Figure 5.** a) Schematic illustration of preparing the cable-shaped Zn–air battery. b) Optical image of cross section of cabled battery. c) GCD curves of load and unload states of battery with stack and cable structures. Reproduced with permission. Copyright 2014, Wiley-VCH. d) The schematic diagram of flexible Zn–air battery. e) High-magnification SEM image of Co$_3$N/carbon fibers/carbon cloth. f) Comparative GCD curves of three types of Zn–air batteries. Reproduced with permission. Copyright 2016, American Chemical Society. g) Diagram of the fabrication process of flexible fibrous Zn–air battery with thin mesoporous Co$_3$O$_4$/N-rGO heterostructured nanosheets. i) Comparable GCD curves of the Zn–air battery with hybrid nanosheets and commonly used catalyst. Reproduced with permission. Copyright 2018, Wiley-VCH.
of different types of (stack-type and cable-type) batteries under loading/unloading states are shown in Figure 5c. Clearly, the air electrode equipped with Fe/N/C-900 showed a higher discharging platform and longer duration, be it in stacked-type or cable-type batteries. The high-performance flexible Zn–air battery was prepared on the basis of flexible electrodes via combining metallic Co/Ni with excellent oxygen evolution reaction efficiency and Co–Ni–C with perfect oxygen reduction reaction capability.[44] The detailed schematic diagram of the Zn-air battery is shown in Figure 5d. The SEM image presented the morphology of the free-standing duplex cathode that consisted of Co3N, carbon fibers, and carbon cloth, where versatile Co3N nanoparticles were embedded into the coarse and porous carbon matrix (Figure 5e). The comparison of galvanostatic charge–discharge (GCD) curves of three different batteries illustrated the small polarization (1.09 V at 50 mA cm−2) and long cycle life (up to 408 cycles) of the as-prepared battery (Figure 5f). In addition, the perfect bendability, twistability, and rechargeability properties render the flexible Zn–air battery a promising candidate for portable and wearable electronics. Instead of monometallic nitride, trimetallic nitride was also used as the air cathode for fiber zinc–air batteries. Nonprecious NiFeMn–nitride sheets were obtained through thermal nitridation of NiFeMn hydroxide–Ti3C2 sheets composite.[45] The incorporation of MXene sheets helps to stabilize the trimetallic nitride sheets and improve the oxygen evolution reaction (OER)/oxygen reduction reaction (ORR) catalytic activity. With the trimetallic nitride sheet as the air cathode, the flexible fiber-shaped zinc–air battery demonstrates high energy density of 627 Wh kg−1. Li et al. reported flexible fibrous Zn–air battery with controlled length for weaving into clothing and textiles for wearable electronics.[46] The success of this battery stemmed from the successful preparation of Co3O4/nitrogen-doped reduced graphene oxide (rGO) hybrid bifunctional nanosheets with a 2D layer-by-layer structure. It has high surface area, large pore volume, and strong synergistic effect between Co3O4 and N-rGO. The fabrication process of the flexible fibrous Zn–air batteries is shown in Figure 5g. Moreover, the designed heterogeneous nanosheets displayed a homogeneous stratified layer-by-layer pattern composed of an upper cobalt-based mesoporous layer and a N-rGO matrix layer, which is shown in Figure 5h. The charge–discharge polarization curves of the prepared fibrous Zn–air batteries are shown in Figure 5i. The hybridized nanosheets-based Zn–air batteries exhibited a relatively low potential gap compared with batteries with Pt/C and RuO2 catalysts, whereby the lower gap indicates better chargeability. Apart from the mentioned research, attempts were applied to study the highly stretchable Zn–air batteries.[47–50] Xu et al. demonstrated the fiber-shaped Zn–air battery with good flexibility, stretchability, and rechargeability, which was constructed from the air cathode with aligned and cross-stacked CNT sheets and RuO2-based catalyst, spring-like zinc anode, and hydrogen polymer electrolyte.[51] All components in this battery were flexible and stretchable, whereas the solid hydrogen polymer electrolyte was simultaneously used as an isolator to protect against short circuits and electrolyte leakage in stretching and bending processes, allowing high flexibility and stretchability.

3.4. Zn–Co/Ni Batteries

The major limitation of Zn–Ag batteries is the high cost of silver electrodes; thus, the new research focus is Zn–Co/Ni batteries, where the Co/Ni oxide/hydroxide-based cathode can be reversibly transformed into oxhydroxide in the alkaline electrolyte. Rechargeable Zn–Co/Ni aqueous batteries with high voltage output, low cost, and excellent safety features have enormous potential for large-scale energy-storage applications.[52] The growing quest for portable and wearable electronics has led to the recognition of small-sized, lightweight, highly flexible, and wearable fibrous Zn–Co/Ni batteries as promising energy supply. Two critical issues have severely impeded their broader applicability. On the one hand, the formation and proliferation of zinc dendrites significantly reduces the cycle life (typically less than 500 cycles). On the other hand, the usage of heavy zinc plates as conventional anodes for zinc-based batteries reduces the energy density and also limits their application in flexible energy-storage devices. Li et al. obtained a three-layer 3D CC-ZnO@C-Zn anode by growing zeolite-imidazole framework (ZIF)-derived ZnO@C core–shell nanospheres on carbon cloth, followed by in situ Zn deposition, which exhibited excellent resistance against dendrite formation.[53] Equipped with branch-shaped Co(CO)3(OH)x0.11H2O@CoMoO4 (CC-CCH@CMO) as the anode, and PVA–KOH as the gel electrolyte, the zinc core–catalyst battery exhibited excellent energy density. The fiber-shaped Zn–Co battery is schematically shown in Figure 6a. The core–shell structure of CC-ZnO@C was formed by coating a layer of ZIF-derived carbon with a thickness of 20–50 nm on ZnO nanorods, as shown in Figure 6b. The GCD curves in Figure 6c indicate high performance of the as-prepared Zn–Co battery, offering maximum capacity of 0.71 mAh cm−2 at current density of 1 mA cm−2. In addition, it delivered a superior performance, including long cycle life (capacity retention of 82% over 1600 cycles) and high energy/power density (4.6 mWh cm−3, 0.42 W cm−3). Huang et al. took advantage of the conductive yarns as the backbone to grow the Zn and Ni/Co hydroxide via the electrodeposition method, which demonstrated the high electrical conductivity and mechanical stability.[54] It was obviously noticed that both Zn and Ni/Co hydroxide were uniformly and densely covered on the whole yarn electrode. With the help of the PVA gel electrolyte, the assembled battery was freestanding, without any binder or separator, as shown in Figure 6d. SEM image further proved that the Zn nanoflakes tightly and intensely coated the surface of yarn-based electrode (Figure 6e). The thin and porous nature of these nanoflakes greatly increased the effective surface area and ensured fast ion transport during charging/discharging, which facilitated fast electrochemical kinetics. The yarn-based battery possessed high specific capacity of 5 mAh cm−3 and superb energy density of 0.12 mWh cm−3 (Figure 6f). Li et al. presented Zn–Ni batteries composed of self-standing fibrous anodes supported by 3D nanotube arrays, in which Zn was deposited as nanoparticles instead of monolithic dendritic crystals, greatly facilitating the electrochemical reaction rate of the anode.[55] The merits of 3D Li-doped TiO2 electrode can elevate galvanic properties during the process of Zn dissolution and deposition, as well as improve the long-term durability. The detailed fabrication process of Zn anode
is shown in Figure 6g, where the flexible Zn–Ni batteries were successfully packaged with the Ni deposited on the copper fiber as cathode. The SEM image in Figure 6h shows that the anode retains its original nanostructure with minor shape change after 3000 cycles, further proving the enhanced durability of the Zn-based anode. The GCD curves in Figure 6i exhibited high specific capacity of 19.6 A cm\(^{-2}\) at current density of 1.4 A cm\(^{-2}\) and stable output plateau of 1.7 V. Moreover, the Ni–Zn battery offered excellent durability of around 95% capacity retention after 20,000 cycles.

Apart from enhancing the Zn-based electrodes, improvements of Ni-based electrodes were also attempted. MOF has been used as a promising electroactive material for electrochemical energy storage due to its versatility, high specific surface area, crystallinity, and porous hybrid properties. Man et al. proposed using Ni-MOF-74 directly grown on the surface of CNT fibers as a binder-free cathode, where the unique honey-shaped structure of Ni-MOF-74 provided more active sites involved in electrochemical reactions and promoted the efficiency of electron transport between the electrode material and electrolyte, resulting in accelerated redox reactions and high specific capacity.\(^{[56]}\) The schematic structure of the as-acquired Ni/Zn battery is shown in Figure 7a, paired with the Zn wire as the anode and KOH–PVA as the gel electrolyte. It is further shown in Figure 7b that Ni-MOF-74 was highly oriented and well distributed on the CNT fiber with a conical structure. The assembled battery acquired good reversibility and high discharge output voltage of 1.75 V as well as high capacity of 184.5 mAh cm\(^{-2}\) at a current density of 0.25 A cm\(^{-2}\) (Figure 7c). Ni-MOF was also applied as the cathode by Li et al.\(^{[56]}\) Ni-MOFs were homogenously distributed on the surface of CNT fibers and the device was fabricated via encapsulating the Zn wire and as-prepared cathode together into a heat-shrinkable tube with KOH aqueous solution as the electrolyte, and the assembled battery is shown in Figure 7d. The SEM image in Figure 7e demonstrated the nanoflake morphology of Ni-MOF. The GCD curves of the battery in Figure 7f showed a high discharge voltage plateau of 1.75 V and good symmetry, reflecting its desirable battery characteristic and excellent electrochemical reversibility. The battery displayed a high areal capacity of 0.44 mAh cm\(^{-2}\) at the current density of 0.5 mA cm\(^{-2}\) and it still retained 0.35 mAh cm\(^{-2}\) when the current density increased ten times, demonstrating superior rate capability.
3.5. Ni–Bi Batteries

Ni-based FRAABs are normally based on the reversible transformation from Ni oxide/hydroxide to Ni oxyhydroxide at the cathode. In Ni–Bi batteries, the anode is based on the conversion of Bi to Bi$_2$O$_3$ in alkaline electrolytes. Assembly of Ni–Bi batteries has been realized through the combination of different cathode/anode materials, e.g., Ni(OH)$_2$/BiO$_2$CO$_3$(OH)$_2$; Ni–Co hydroxide/Bi$_2$O$_3$; NiO/highly crystalline Bi superstructures; NiO/Bi$_2$O$_3$; Ni–NiO/Bi nanoflakes; etc. Various approaches have been adopted to improve the electrochemical performance of Bi-based anode in Ni–Bi batteries. Partial surface oxidation of Bi nanoflakes was found out to create more active sites and lower the free energy of OH adsorption, leading to better electrochemical reversibility, with enlarged capacity and extended cycling stability of the Bi anode. Highly crystalline Bi superstructures obtained from thermal annealing were found to demonstrate smaller charge transfer resistance than the nonannealed Bi anode, realizing improved capacity and cycling stability. As a result, Ni–Bi batteries with excellent cycling stability of 10 000 cycles were assembled. Fe was incorporated in Bi oxide anode, forming BiFeO$_3$ anode for Ni–Bi batteries. Introduction of Fe mitigated the phase transformation and fusing issues, thus improving the capacity and cycling stability (81.2% after 2000 cycles) of the anode. The approaches discussed here were adopted in the conventional sandwich-structured Ni–Bi batteries; however, they are regarded to be as effective as in fiber-shaped Ni–Bi batteries. A novel fiber-shaped Ni–Bi battery with remarkable electrochemical performance was prepared by the layered 3D electrodes, in which rGO sheets with a Bi framework served as the anode and rGO sheets encasing Ni/NiO featured as the cathode. The detailed preparation process of rGO/Bi/CNT anode is shown in Figure 8a, where the rGO sheets were directly coated on the CNT fibers. SEM image of the anode in Figure 8b further proved that the rGO and Bi nanoparticles were densely deposited on the CNT to form the hierarchical 3D electrode. This anode possessed high capacity of 146.9 mAh g$^{-1}$ at 1 A g$^{-1}$ with capacity retention of about 73% as the current density increased to 25 A g$^{-1}$ (Figure 8c). As for the cathode material, the same electrodeposition method was used to grow rGO/Ni/NiO hybrids on the CNT fibers. As shown in Figure 8d, the rGO and Ni/NiO nanoparticles were dispersed on the surface of CNT. In addition, the cathode delivered high capacity of 114.5 mAh g$^{-1}$ at 5 A g$^{-1}$ (Figure 8e). The fibrous Ni–Bi battery was manufactured by packing the rGO/Bi/CNT anode and rGO/Ni/NiO/CNT cathode together (Figure 8f). The as-assembled battery achieved excellent specific capacity of 163.7 mAh g$^{-1}$ at 5 A g$^{-1}$, as well as stable charging plateau, suggesting an effective redox reaction (Figure 8g).

3.6. Ni–Fe Batteries

Ni–Fe batteries are being extensively studied on account of their invulnerability (overcharging, overdischarging, and indiscrimination), long cycle time, and shelf life. Moreover, higher safety, lower cost, higher ionic conductivity of the electrolyte, free dendrite formation, and insignificant environmental side effects of aqueous Ni–Fe batteries have turned them into a worldwide research hotspot. The electrochemical mechanism of the Fe-based anode is normally based on the reversible conversion from Fe/Fe$_2$O$_3$ to Fe hydroxide. Considerable progress has recently been made in the development of Fe-based anodes for Ni–Fe batteries.
batteries through the design of nanostructures, interfacial engineering, and heteroatom doping, thereby raising the intrinsic capacity and energy density. It is known that the characteristics of nanomaterials depend on the size and morphology. For instance, the specific surface area of metal particles increases with the decrease in particle size, as this plays an influential role in the catalysis. Liu et al. fabricated the superstructured $\alpha$-Fe$_2$O$_3$ nanorods with further polypyrrole (PPy) coating to optimize the electron/ion transportation and cycling stability. With the CoNiO$_2$@Ni(OH)$_2$ nanowire arrays as the cathode and KOH–PVA as the gel electrolyte, the fiber-shaped Ni–Fe battery was installed, as shown in Figure 9a. The SEM images of Fe$_2$O$_3$@PPy/CNT fibers are shown in Figure 9b. Notably, the Fe$_2$O$_3$ nanoplate arrays homogeneously occupied the entire surface of CNT fibers. There are significant amounts of vacancies and channels contained in the 3D superstructured $\alpha$-Fe$_2$O$_3$ nanorods, which can effectively shorten the electron/ion migration paths. In addition, a wealth of channels facilitates ion interaction with the internal active material, thus improving the electrochemical properties. The fabricated battery offered an excellent capacity of 0.62 Ah cm$^{-2}$ at 1 A cm$^{-2}$, with notable cycling and mechanical stability (Figure 9c). Zhang et al. proposed making use of the all-MOF-derived electrodes with the NiZnCoP nanosheet arrays as the cathode and spindle-like $\alpha$-Fe$_2$O$_3$ as the anode to fabricate the high-performance fiber-shaped Ni–Fe battery (Figure 9d). MOFs are considered prosperous substrates for the formation of porous materials with a well-tuned structure and large surface area. Figure 9e shows the symmetric distribution of spindle Fe$_2$O$_3$ on the CNT fiber surface. By means of spindle structures, a larger surface area of the Fe$_2$O$_3$/CNT fiber can provide more active sites. GCD curves in Figure 9f at various current densities showed two distinct plateaus of 1.35 and 1.05 V, respectively. High capacity of 0.092 mA cm$^{-2}$ was achieved at the current density of 1 mA cm$^{-2}$. TiN nanowire arrays were demonstrated as potential substrates for the growth of other active materials due to their high electron mobility, high bulk-to-volume ratio, outstanding mechanical capacity, and excellent thermal stability. Subsequently, well-oriented Fe$_2$O$_3$ nanorods were uniformly spread on the TiN nanowire arrays. For the cathode, the similar core–shell-structured NiCoP@NiCoP was also applied to fabricate the high-performance battery (Figure 9g). The unique core–shell heterogeneous structure was further depicted in SEM images (Figure 9h), where a uniform arrangement of Fe$_2$O$_3$ on the TiN surface and the dense and subtle
expansion of the composite along the axis of the 3D skeleton were visualized. Notably, apparent plateaus near 1.22 and 1.08 V were observed during discharge and charging, respectively (Figure 9i). Also, the assembled Ni\textsubscript{2}/C0\textsubscript{Fe} battery had an ultrahigh capacity of 0.77 mAh cm\textsuperscript{-2} at a current density of 2 mA cm\textsuperscript{-2}.

Modulation of the morphology of Fe\textsubscript{2}O\textsubscript{3} allows augmented specific surface area, thus achieving reduced ion diffusion length and enhanced capacity of Fe\textsubscript{2}O\textsubscript{3} electrodes. There have been attempts to optimize the kinetics intrinsically through ion doping. This is considered to be an effective method to increase the capacity by adding anionic or cationic ions to the Fe\textsubscript{2}O\textsubscript{3} lattice. It is believed that a defective or local impurity energy level is introduced by ion doping into the lattice. At the same time, with the introduction of a large number of vacancies, more electrolyte can be absorbed. The introduction of metallic ions allows bandgap optimization and sometimes change in the original morphology and phase structure, so as to speed up the carrier transport. The doping of Mn into Fe\textsubscript{2}O\textsubscript{3} was conducted by Jin et al. to improve the electrochemical performance and durability.\textsuperscript{[68]} The schematic structure of Mn-doped Fe\textsubscript{2}O\textsubscript{3} is shown in Figure 10a, with successful substitution of Mn atoms for Fe atoms, therefore leading to several lattice defects. In Figure 10b, SEM images distinctly showed the vertical and uniform growth of Mn–Fe\textsubscript{2}O\textsubscript{3} nanoplates. As shown in Figure 10c, the device acquired a high capacity of 46 mAh cm\textsuperscript{-3} at 2.5 A cm\textsuperscript{-3} when matched with Mn–NiO cathode. Nonmetallic elemental doping usually induces oxygen lattice vacancies or partial replacement, resulting in a narrow bandgap. Sulfur atom lies within the same main group of oxygen and requires low formation energy to replace the oxygen atom in the nonmetallic doping process; hence, it is widely used for modifying the electronic structure. Yang et al. calculated the bandgap of Fe\textsubscript{2}O\textsubscript{3} materials, where it decreased from 2.34 to 1.18 eV after sulfur doping, resulting in improved electronic conductivity.\textsuperscript{[69]} It is clearly shown in Figure 10d that the oxygen atom was partially replaced by the sulfur atom. Compared with undoped Fe\textsubscript{2}O\textsubscript{3}, the SEM image of S-Fe\textsubscript{2}O\textsubscript{3} appeared to be marginally different, with Fe\textsubscript{2}O\textsubscript{3} nanowires distributed vertically on the surface of the CNT fiber, as shown in Figure 10e. Equipped with the high-performance cathode material of ZNCO@Ni(OH)\textsubscript{2}, the
Ni–Fe battery delivered high capacity of 0.46 mAh cm$^{-2}$ at the current density of 4 mA cm$^{-2}$ as well as a very steady voltage output plateau (Figure 10f).

4. Conclusion and Perspectives

In summary, increasing emphasis has been put on the development of FRAABs to better accommodate various drastic deformations required to cater to the growing demand for energy storage in portable and wearable electronic devices. This Review presents a rigorous summary on state-of-the-art FRAABs from the perspective of novel design principles, electrode materials, and device fabrication. Up to now, several energy-storage mechanisms have been successfully implemented in FRAABs, yielding promising performance. Numerous efforts will continue to pursue improved electrochemical properties, mechanical flexibility, and robustness, while enabling wider adoption of FRAABs in the advent of the era of Internet of Things, where new materials will be rapidly developed and devices will be manufactured with less overall fabrication cost.

4.1. Electrochemical Performance

Although FRAABs have made significant improvement in both capacity and cycling performance, by far, they are still inferior in theoretical energy density. In this regard, the unique fibrous structure, while offering the required flexibility, also presents impediments to performance improvement. First, 1D models with high-curvature interfaces can lead to stripping of the active material, thereby reducing the active material mass loading and decreasing the electrode utilization. The capacity of individual FRAABs is relatively low with respect to their flexible planar counterparts. Usually, the excellent flexibility is attained by substituting the mass loading of the active material, which leads to a lower capacity. Therefore, it is necessary to make a trade-off between the mass loading of the active material and the flexibility of the device to further improve the energy-storage capacity of a single FRAAB. As a second point, high internal resistance of fibrous batteries is conferred by the high-aspect-ratio structure and gel electrolyte. Both the large specific surface area and high electrical conductivity of the fiber electrodes are essential for improved battery performance. In contrast to metallic wire electrodes with high conductivity (at the level of $10^5$ S cm$^{-1}$) but low specific surface area and poor loading capacity, carbon-based fiber electrodes provide better specific surface area and loading ability with comparable conductivity (at the level of $10^2$–$10^3$ S cm$^{-1}$). Most of the current fibrous alkaline rechargeable batteries can efficiently operate at the length of the centimeter level, which remains quite limited for consecutive knitting/weaving processes. The utilization of high-specific-surface-area metal fiber collectors to obtain high conductivity and the development of innovative in situ manufacturing approaches with reduced interfacial resistance are valid strategies to preserve electrochemical performance while extending the device length.

4.2. In Situ Characterization of Energy-Storage Mechanisms

With FRAABs regarded as potential candidates for wearable energy-storage devices, studies are currently in their early stages...
and numerous technical barriers persist. The most critical one is the deficiency in understanding the underlying electrochemical processes in response to exterior mechanical stresses. This is typically concerned with sequences of fundamental electric charge and mass exchange processes occurring along surfaces, across interfaces, and through certain phases of the bulk electrodes, making it difficult to determine the speed-limiting stages. With the aim of illuminating the mechanisms and determining the speed-limiting stages, the tracking of the structure, configuration, and morphology of the electrodes as well as the evolving charge and mass transportation during operation and deformation has to be conducted. An in situ characterization tool is required to detect the electrode structure, composition, and morphology in operational conditions for relating these microscopic characterizations to electrochemical properties. Nowadays, there are plenty of in situ characterization techniques to reveal the structural/physical/chemical variations of different energy-storage systems. However, different in situ characterization techniques are endowed with respective advantages and drawbacks. For example, in situ X-ray diffraction can reveal the crystal structure variations of the electrode materials during charging/discharging, but it can hardly reveal any information for amorphous materials. Nonetheless, in situ X-ray absorption fine structure is suitable for both crystalline and amorphous materials. In situ nuclear magnetic resonance can detect the local chemical changes, but it is not suitable for zero-spin nuclei. Other than in situ characterization methods, including transmission electron microscopy (TEM) and atomic force microscopy (AFM), might not be suitable for FRAABs. In situ TEM is operated under high vacuum; thus, the aqueous alkaline electrolyte in FRAAB should be avoided. The AFM tip should be in close contact with the electrode surface, and the widely used gel electrolyte in FRAAB will surely cause extreme difficulty in doing so.

4.3. Safety and Washability

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For most of the reported works on FRAABs, the batteries were manually assembled. In practical production, the batteries have to be woven and knitted into textiles with the help of weaving/knitting machines. However, inevitable tensile stress as well as frictions will be imposed, causing breakage or detachment in the FRAABs. The tensile stress can be as high as 400–800 MPa, which is much higher than those of the fiber electrodes made of graphene/CNTs (10°2–10°3 MPa). Metallic wires-based fiber substrates can sustain such tensile stress, yet the smooth surface cannot guarantee good adhesion between active materials and the metallic wires. As a result, the mechanical flexibility of FRAABs should be carefully evaluated before being transferred to real applications. The mechanical properties of the fiber substrates, adhesion between active materials with the substrates, and the device integrity should be considered so as to realize practical applications. Practical wearables inevitably bring FRAABs into physical contact with the human body. Therefore, it is critical to ensure an absolute safety of these batteries. Primary concern is the corrosive nature of the alkaline gel electrolyte. Valid packaging is extremely important for FRAABs in real applications. Encapsulation of fibrous counterparts featuring high-curvature interfaces is an even more challenging process than for planar devices, in particular for Zn–air batteries with air cathodes needing air exposure. In addition, these FRAABs must be capable of withstanding washing or perspiration penetration once they are integrated into wearable fabrics or textiles. In the future, thermal drawing technique will represent an attractive approach to encapsulate FRAABs to improve their reliability and washing ability.

4.4. Scalable Production and Practical Applications

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The manufacturing process for FRAABs is more rigorous and complex than that for planar batteries. It mainly stems from the interdependence between 1D geometry and finite degrees of freedom, when considering the alignment of battery versatility, adaptation, and capability. In consequence, the performance of FRAABs has been merely focused on the centimeter level; however, such a method does not have the practical value for actual applications. For the large-scale and low-cost manufacturing of FRAABs, a simple, controlled, and efficient method to prepare electrodes is the first stage. The manufacturing difficulty will increase significantly as the device elongates. Another important concern for practical production that should be highlighted is the cost of manufacturing. It is significant to scale up fabrication in a low-cost and high-throughput manner, but the realization is currently difficult. Furthermore, valid criteria for electrochemical performance evaluation and assessment are required, which means that the energy density of FRAABs is typically calculated in terms of the total mass of the active material instead of the total mass of the fiber device.

4.5. Future Directions

4.5. Future Directions
Despite the issues and difficulties that the FRAABs are facing toward real applications, the future of FRAABs remains promising. There are a few directions to be considered to facilitate the adoption of FRAABs into the market. First, the energy density and power density of FRAABs should be improved, by improving the loading mass, charge balance between cathode/anode, utilizing gel electrolyte with a large voltage window, etc. Second, the fabrication process of FRAABs should be cost effective and facile. Although some of the reported FRAABs manifest their outstanding electrochemical performance, the process is not suitable for large-scale production due to the costly raw materials and complex procedures involved. Third, the device integrity of FRAABs should be ensured to sustain possible stress induced during production process. Large-scale production of FRAABs requires the assistance of equipment. For example, in the textile industry, weaving/knitting machines will be used to produce FRAABs-based fabrics, yet tensile stress and frictions will possibly cause failures in FRAABs. Finally, it is possible to integrate multifunctionality into FRAABs to expand the application scenarios. With the earlier directions considered, it is believed that the FRAABs will soon embrace wider applications.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.
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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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[1] S. Hong, S. Myung, Nat. Nanotechnol. 2007, 2, 207.
[2] T. Q. Trung, S. Ramasundaram, B. U. Hwang, N. E. Lee, Adv. Mater. 2016, 28, 502.
[3] W. Liu, M. S. Song, B. Kong, Y. Cui, Adv. Mater. 2017, 29, 1603436.
[4] J. Liu, C. Guan, C. Zhou, Z. Fan, Q. Ke, G. Zhang, C. Liu, J. Adv. Mater. 2016, 28, 8732.
[5] Y. Zeng, Z. Lin, Y. Meng, Y. Wang, M. Yu, X. Lu, Y. Tong, Adv. Mater. 2016, 28, 9188.
[6] L. Ma, S. Chen, H. Li, Z. Ruan, Z. Tang, Z. Liu, Z. Wang, Y. Huang, Z. Pei, J. A. Zapier, Energy Environ. Sci. 2018, 11, 2521.
[7] C. Li, Q. Zhang, J. Sun, T. Li, S. E, Z. Zhu, B. He, Z. Zhou, Q. Li, Y. Yao, ACS Energy Lett. 2018, 3, 2761.
[8] C. Guan, W. Zhao, Y. Hu, Q. Ke, X. Li, H. Zhang, J. Adv. Energy Mater. 2016, 6, 1601034.
[9] D. Chao, C. Zhu, M. Song, P. Liang, X. Zhang, N. H. Tiek, H. Zhao, J. Wang, R. Wang, H. Zhang, Adv. Mater. 2018, 30, 1803181.
[10] Y. Zeng, X. Zhang, Y. Meng, M. Yu, J. Yi, Y. Wu, X. Lu, Y. Tong, Adv. Mater. 2017, 29, 1700274.
[11] Y. Zeng, X. Zhang, R. Qin, X. Liu, P. Fang, D. Zheng, Y. Tsong, X. Lu, Adv. Mater. 2019, 31, 1903675.
[12] F. Meng, H. Zhong, D. Bao, J. Yan, X. Zhang, J. Am. Chem. Soc. 2016, 138, 10226.
[13] Y. Xu, Y. Zhang, Z. Guo, J. Ren, Y. Wang, H. Peng, Angew. Chem., Int. Ed. 2015, 127, 15610.
[14] J. Yin, Y. Li, F. Lv, Q. Fan, Y.-Q. Zhao, Q. Zhang, W. Wang, F. Cheng, P. Xi, S. Guo, ACS Nano 2017, 11, 2275.
[15] H. Li, Z. Liu, G. Liang, Y. Huang, Y. Huang, M. Zhu, Z. Pei, Q. Xue, Z. Tang, Y. Wang, ACS Nano 2018, 12, 3140.
[16] Y. Huang, W. S. Ip, Y. Y. Lau, J. Sun, J. Zeng, N. S. S. Yeung, W. S. Ng, H. Li, Z. Pei, Q. Xue, ACS Nano 2017, 11, 8953.
[17] Z. Guo, Y. Zhao, Y. Ding, X. Dong, L. Chen, J. Cao, C. Wang, Y. Xia, H. Peng, Y. Wang, Chem 2017, 3, 348.
[18] P. Yu, L. Wang, F. Sun, Y. Xie, X. Liu, J. Ma, X. Wang, C. Tian, J. Li, H. Fu, Adv. Mater. 2019, 31, 1901666.
[19] Y. Zhang, Y. Wang, L. Wang, C.-M. Lo, Y. Zhao, Y. Jiao, G. Zheng, H. Peng, J. Mater. Chem. A 2016, 4, 9002.
[20] Q. Zhang, Z. Zhou, Z. Pan, J. Sun, B. He, Q. Li, T. Zhang, J. Zhao, L. Tang, Z. Zhang, Adv. Sci. 2018, 5, 1801462.
[21] B. He, Q. Zhang, P. Man, Z. Zhou, C. Li, Q. Li, L. Xie, X. Wang, H. Pang, Y. Yao, Nano Energy 2019, 64, 103935.
[22] Q. Zhang, L. Li, H. Li, L. Tang, B. He, C. Li, Z. Pan, Z. Zhou, Q. Li, J. Sun, Nano Energy 2019, 60, 267.
[23] Q. Zhang, P. Man, B. He, C. Li, Q. Li, Z. Pan, Z. Wang, J. Yang, Z. Wang, Z. Zhou, Nano Energy 2020, 67, 104212.
[24] Y. Zeng, Y. Meng, Z. Lai, X. Zhang, M. Yu, P. Fang, M. Wu, Y. Tong, X. Lu, Adv. Mater. 2017, 29, 1702698.
[25] A. M. Zamarayeva, A. E. Ostfeld, M. Wang, J. K. Duey, I. Deckman, B. P. Léchène, G. Davies, D. A. Steingart, A. C. Arias, Sci. Adv. 2020, 6, eabg5697.
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