

Research Highlight

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# Revolutionizing fiber batteries with polymer gel electrolyte: a groundbreaking innovation in wearable energy

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The advent of flexible and wearable electronic devices heralds a transformative era in consumer electronics and personalized health monitoring. As these devices become increasingly integrated into our daily lives, there is a pressing need for the development of energy storage or conversion systems with the merits of high performance, small size, and adaptability to frequent deformation during usage. Among these power sources (such as batteries, supercapacitors, fuel cells, and solar cells)<sup>[1,2]</sup>, batteries, with lithium-ion batteries being a prime example, have been known for several decades as devices that convert stored chemical energy directly into electricity<sup>[3,4]</sup>. To date, they are among the most widely used power supplies for electronic devices and have become an integral part of modern electronics. However, for the booming smart textiles, integrating batteries into textiles remains a critical challenge. Traditional rigid batteries are rigid and unsafe; they are not suitable for the inherently soft and flexible nature of smart textile technology<sup>[5]</sup>.

Fiber lithium-ion batteries (FLBs) stand out for their unique benefits, particularly in the context of wearable technology and energy textiles. Their compatibility with the textile industry is a key advantage, as they can be seamlessly integrated into fabrics as functional yarns, enhancing the versatility of energy textiles.



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Additionally, these batteries offer improved air permeability compared to conventional planar batteries, which are often impermeable and resemble leather. This feature addresses a significant limitation in current battery design. Furthermore, the inherent flexibility and miniaturization potential of fiber-shaped batteries enable the creation of diverse, flexible power sources that can be tailored to various applications, providing unmatched adaptability and innovation potential in the field of energy storage. Through an optimized scalable industrial process, meters of FLBs have been produced in a continuous way<sup>[6]</sup>. From the perspective of practical application, there are still great requirements and challenges for batteries, which mainly include: (1) the difficulty in controlling the flexibility to ensure wear comfort while achieving stable electrochemical properties, especially during battery deformation; (2) and increased safety hazard, as these devices are subjected to more frequent dynamic deformation during use, raising the possibility of mechanical damage.

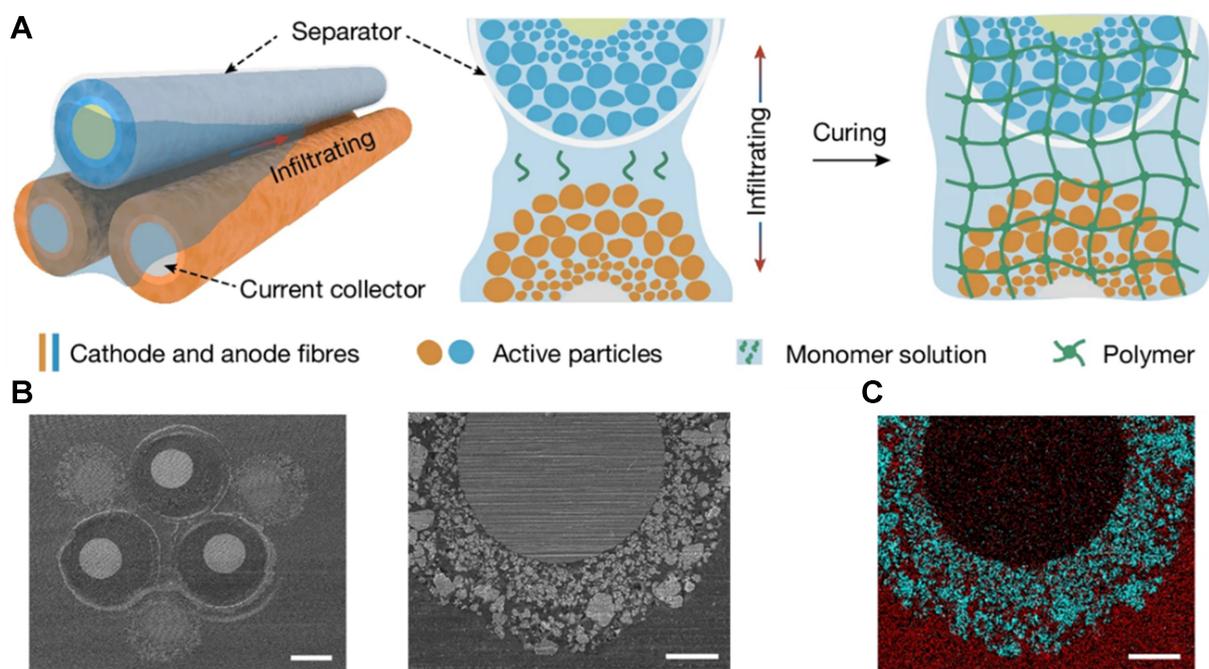
To enhance the safety profile and facilitate practical deployment of FLBs, researchers have explored the use of gel electrolytes as a substitute for traditional liquid electrolytes<sup>[5,7-10]</sup>. However, this substitution has been met with challenges. With an absence of chemical bonding to current collectors, gel electrolytes exhibit limited infiltration into the electrode materials, which leads to a suboptimal gel electrolyte-electrode interface. This issue significantly impacts the energy density of FLBs, often resulting in values well below the desired threshold, typically less than 10 Wh·kg<sup>-1</sup>.

The challenge for achieving reliable electrochemical performance lies in the inconsistent interface contact between the polymer gel electrolytes and the fiber electrodes, particularly under dynamic deformation. To address these challenging issues, building on their previous achievements on the assembly of FLBs<sup>[11-13]</sup>, Lu *et al.* have recently unveiled an innovative design that introduces a channel structure within the electrodes. This design serves to effectively integrate polymer gel electrolytes, creating intimate and stable interfaces that are crucial for the development of high-performance batteries<sup>[14]</sup>.

As shown in [Figure 1](#), the small active particles are firstly deposited onto thin fiber current collectors and followed by larger ones, which results in the formation of a layered network of inner small and outer large channels among the particles. By rotating multiple cathode and anode fibers in conjunction with separators and introducing a monomer solution into these aligned and interconnected channels, robust and efficient gel electrolyte-electrode interfaces were produced after subsequent polymerization.

Such aligned channels have been shown to markedly expedite the permeation of electrolytes, a critical factor in optimizing energy storage device performance. Specifically, the internal micro-architecture, composed of smaller particles, adeptly facilitates electrolyte collection along the sinuous profiles of fibers, thereby diminishing interfacial impedance and hastening ion intercalation during high-rate discharge. In stark contrast, the larger particles on the exterior surface exhibit enhanced reversibility in the lithium-ion intercalation-deintercalation process. This characteristic is paramount for achieving elevated Coulombic efficiency and a notable increase in specific capacity, thereby reinforcing the role of particle size stratification in the advancement of electrochemical properties.

Concurrently, the larger particles on the outer layers enhance the battery's Coulombic efficiency and contribute to a high specific capacity output. As a result, The FLBs showed a high energy density of up to about 128 Wh·kg<sup>-1</sup> and maintained high capacity even under a high production rate of 3,600 m·h<sup>-1</sup>. It is also critical to highlight that, in addition to the impressive electrochemical properties, their devices also demonstrated great stability and safety under various test conditions. Owing to the stable electrolyte-electrode interface, the FLB demonstrated remarkable flexibility and stability, withstanding an impressive 100,000 bending cycles. It also exhibited resilience in extreme conditions, such as operating temperatures



**Figure 1.** (A) Schematic illustration; (B) cross-sectional SEM image and (C) EDS elemental mapping of an FLB. The Active particles and networked channels on the cathode and anode fiber surface can be observed<sup>[14]</sup>. Credit: Springer Nature. SEM: Scanning electron microscopy; EDS: energy-dispersive X-ray spectroscopy; FLB: fiber lithium-ion battery.

ranging from 0 to 80 °C, underwater environments, exposure to ultraviolet light, and even functioning in a vacuum at -0.08 MPa. These robust characteristics show a great performance improvement [Table 1], and indicate that FLBs possess considerable potential for a variety of demanding applications, including firefighting and space exploration.

In summary, this work by Lu *et al.* provides an unprecedented strategy for closely and stably interfacing polymer gel electrolytes with electrode fibers, offering advantages such as higher power and energy densities, improved productivity and significantly enhanced safety for FLBs<sup>[14]</sup>. Their groundbreaking discovery propels the field of wearable battery technology forward, which opens up new possibilities for flexible electronics, biomedical engineering, space exploration, and wearable technology, marking a significant stride in the evolution of portable and adaptable energy solutions.

Despite significant advancements in FLBs, further enhancement in battery performance, flexibility, and assembly remains crucial for various application fields, such as wearable medical equipment or aerospace flexible energy systems. Building on this foundation, several in-depth strategies for electrolyte improvement have been proposed and thoroughly discussed:

- (1) High performance is fundamental for battery applications; thus, developing lightweight, and electrochemically superior active materials is vital.
- (2) Fibers are the building blocks of textiles to provide a soft and comfortable feel. Despite this, fiber-shaped batteries often lack the softness of natural fibers, exhibiting a texture more similar to plastic threads.

**Table 1. Performance comparison of different FLBs**

Fiber battery	Specific capacity	Energy density	Stability assessment	Ref.
FLBs (2021)	Between 160 and 180 mAh·g <sup>-1</sup> at 0.1 C	85.69 Wh·kg <sup>-1</sup>	93% capacity retention at 1 C rate; > 80% capacity at 100,000 bending cycles; strong environmental adaptability (-20 to 60 °C)	[6]
FLBs (2022)	86 mAh·g <sup>-1</sup> at 50 mA·g <sup>-1</sup>	550 mWh·m <sup>-2</sup>	Stable performance after 10,000 bending cycles; stable performance after bending, knotting, and twisting heat resistant (300 °C); good environmental adaptability (workable after puncture)	[11]
FLBs (2023)	14.97 mAh	62 Wh·kg <sup>-1</sup>	85.8% capacity retention after 10,000 bending cycles	[15]
FLBs (2023)	Linear specific capacity, 0.26 mWh·cm <sup>-1</sup>	106.85 mWh·cm <sup>-3</sup>	94.8%/1 C/1,000 bending cycles, good durability	[16]
FLBs (2024)	170 mAh·g <sup>-1</sup>	128 Wh·kg <sup>-1</sup>	Stable performance after 100,000 deformation cycles; stable performance in 40-80 °C environments	[14]

FLBs: Fiber lithium-ion batteries.

(3) Fabric is the key medium for FLB applications, yet seamlessly incorporating FLBs into breathable energy textiles presents a notable challenge under current technological constraints.

## DECLARATIONS

### Authors' contributions

Wrote and revised the manuscript: Wang H, Yan W, Zhu M

### Availability of data and materials

Not applicable.

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### Conflicts of interest

All author declared that there are no conflicts of interest.

### Ethical approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

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