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Composite Materials COMMENTARY

Weavable power: Advancing fiber fuel cells through Yarn@gels

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Wearable electronics extend computing and sensing into everyday life by continuously monitoring physiology, tracking activity, enabling communication, and supporting human-environment interaction directly on the body. Within this landscape, electronic textiles stand out by embedding electronic functions into fibers and fabrics, offering seamless integration with clothing, soft conformability to body contours, breathability, and unobtrusive aesthetics that favor long-term, everyday wear. Achieving these benefits in practice hinges on the power supply: flexible, lightweight, and durable batteries that can bend, drape, and integrate into textile structures are crucial to preserve comfort and reliability while providing sufficient energy and power for real-world use. Fiber-shaped batteries offer a compelling candidate due to their intrinsic compatibility with fabrics and straightforward integration into textile structures.[1] However, many existing fiber batteries still suffer from relatively low energy density and constrained power output.

Fuel cells, with inherently high energy density and rapid refueling capability, have long been regarded as promising power sources for flexible electronics. In particular, the theoretical energy density of methanol-based fuel cells (≈1000 Wh kg^{-1}) exceeds that of most fiber lithium-ion batteries (10–20 Wh kg^{-1}) by more than an order of magnitude, underscoring fuel cells as a necessary pathway to overcome the intrinsic energy-density bottleneck rather than merely a parallel alternative. Conventional fuel cells, however, remain constrained by complex encapsulation procedures and poor mechanical adaptability, as they often require rigid end plates and other components to maintain integrity.[2] These limitations underscore the need for alternative strategies that can simultaneously deliver high energy density, mechanical stability, and true compatibility with the deformable nature of textiles.

A recent study in *Nature Materials* proposes an adaptive internal-pressure encapsulation strategy—Yarn@gels—that addresses these limitations.[3] In this design, cotton yarns embedded in a gel matrix absorb methanol fuel and swell, generating a uniform internal pressure that automatically seals the electrode interfaces and stabilizes the device architecture (Figure 1). This internal pressure arises from solvent absorption–induced osmotic swelling within the polymer gel, which adaptively tolerate swelling strain through synergistic crosslinked architecture. Unlike traditional rigid sealing by rigid end plates, the Yarn@gels architecture produces self-regulated internal pressure that maintains electrode contact and prevents fuel leakage under deformation, effectively coupling mechanical compliance with electrochemical integrity. The gel simultaneously serves as both the fuel reservoir and internal pressure initiator. This self-sealing design eliminates the need for external encapsulation while preserving flexibility, enabling lightweight construction and direct integration into textiles, thereby simplifying fabrication and ensuring structural integrity without bulky components.

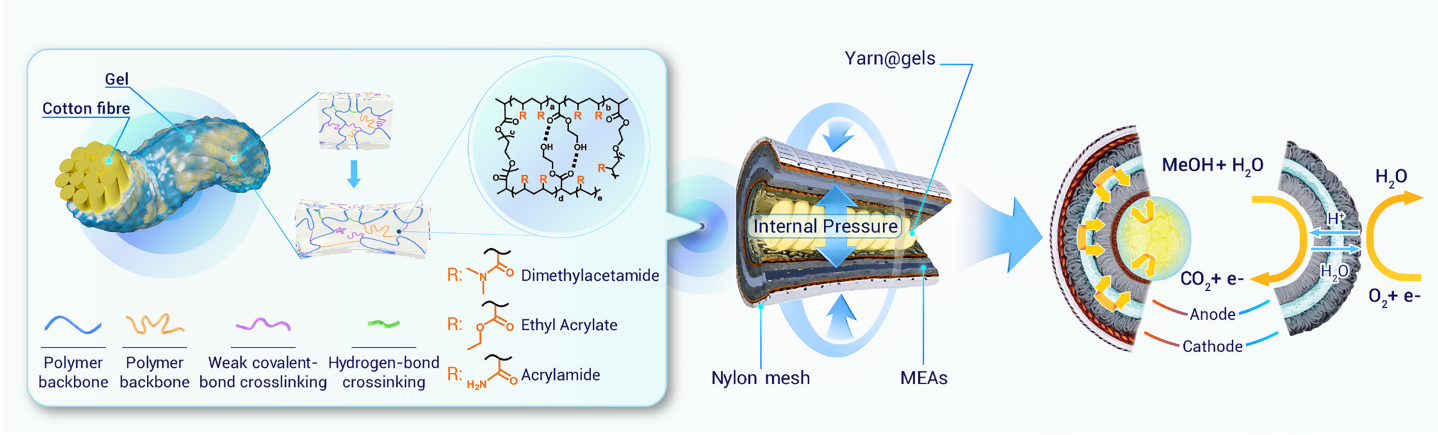

Figure 1. Structure and working principle of fiber-shaped direct methanol fuel cells (FDMFCs) with Yarn@gels architecture.

Beyond mechanical advantages, this approach significantly enhances both electrochemical performance and operational safety. The achieved discharge energy density (161 Wh kg^{-1}) is roughly an order of magnitude higher than that of typical fiber lithium-ion batteries (10–20 Wh kg^{-1}), highlighting the value of shifting from conventional fiber batteries to fuel-cell architectures. Fiber-shaped direct methanol fuel cells (FDMFCs) built with Yarn@gels also deliver a peak power density of 9.68 mW·cm^{-2}, which is 4.4 times higher than that of devices lacking pressure regulation (2.19 mW·cm^{-2}). The devices maintained stable operation under bending, while the detected methanol vapor concentration remained as low as 1.4 mg·m^{-3}, well below occupational exposure limits. Together, these findings demonstrate that adaptive internal-pressure encapsulation effectively reconciles flexibility with high performance, paving the way for the direct integration of fuel cells into wearable textiles.

The FDMFCs also demonstrated reliable performance under mechanical and environmental stress. Power density remained essentially unchanged across bending angles, and devices retained functionality after 2000 bending cycles. They continued to operate following cutting, puncturing, and water exposure. In addition, polarization and power-density measurements confirmed reliable low-temperature start-up and high-temperature tolerance (−22°C to 70°C). Performance was also insensitive to humidity (0–100% relative humidity), with deviations below 4%. This resilience is critical for wearables subjected to daily deformation and variable environments. The design is also scalable: fibers were woven into meshes or stacked linearly to deliver tunable voltage and current, enabling demonstrations such as powering clocks, light-emitting devices, and miniature vehicles—illustrating the feasibil-

ity of textile-integrated energy platforms.

Collectively, the work advances energy density, power delivery, mechanical robustness, and environmental stability, indicating that fiber fuel cells can move beyond one-off prototypes toward practical building blocks for smart textiles and wearable electronics. Looking ahead, several improvements will accelerate real-world deployment.

First, the methanol fuel central to current design offers high energy density, and managing its toxicity and flammability in open-air, textile-integrated use is a key engineering focus. Ensuring safe storage, preventing leakage, and guaranteeing long-term safety are critical for systems operating in close proximity to the human body.[4] Although lower-toxicity fuels and improved fuel-management strategies are under active investigation, mature solutions that preserve high energy density while meeting stringent safety requirements are still emerging. Future developments in advanced encapsulation materials and intelligent fuel delivery systems are likely to further enhance operational safety in textile-integrated applications.

Second, although internal-pressure encapsulation delivers substantial gains, the absolute power output still lags behind that of mainstream solid-state batteries. The current performance is well suited for low-power sensors, basic medical monitors, and simple wearable electronics. Further advances in catalyst activity, ion-conducting membranes, and interfacial engineering will be critical to narrowing this gap.

Third, long-term stability and manufacturability warrant comprehensive validation. While single fibers show resilience under bending and environmental perturbations, durability and encapsulation uniformity within complex woven fabrics remain to be established.[5] Mechanical heterogeneity in textiles can induce local stress and non-uniform reaction kinetics, potentially reducing efficiency and accelerating localized failure—underscoring the need for targeted design and testing. From a production perspective, Yarn@gels fabrication currently relies on precise formulation, ultraviolet curing, and multilayer assembly; thus, process integration and scalable manufacturing strategies will be essential to ensure cost-effective and reproducible fabrication.

In conclusion, Yarn@gels shows that self-regulated internal pressure can reconcile high electrochemical performance with the softness and breathability textiles require, but translating this advance into everyday garments demands a sharper, forward-looking agenda focused on three scientific challenges and the collaborations to address them. First, fuel safety: adopt safer fuels (bioethanol or formic acid) paired with highly selective, low-permeability membranes and could reduce toxicity and crossover while maintaining energy density. Second, automated, continuous reel-to-reel gel coating and curing system based on commodity yarns to ensure uniform internal pressure and cell performance. Third, durability: use interfacial and materials engineering to improve the reliability of fuel cell and validate the performance through standardized textile tests (abrasion, pilling, laundering, sweat corrosion). Progress will be accelerated by tightly bridging materials and textile engineering: multifunctional catalysts, three-dimensional porous electrodes, ion-selective coatings, and advanced conductive fibre scaffolds to raise power and stability. We envision consortia uniting electrochemists, polymer and membrane scientists, textile engineers, safety specialists, and device designers to deliver open datasets, standards, and reference designs. Achieving safe, manufacturable, and durable fibre fuel cells will enable comfortable textiles that continuously power wearable electronics, advancing electronic textiles from niche prototypes to dependable everyday infrastructure.

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DECLARATION OF INTERESTS

The authors declare no competing interests.