

Review

Electrospun Nanofibers for Wearable Electronics: Mechanism, Material, Structure and Application

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Abstract: Smart wearable devices represent the central research thrust in flexible electronics, with broad application prospects in physiological health monitoring, energy harvesting, and human–machine interaction. Nanofibers (NFs), endowed with ultrahigh specific surface area, tunable microstructure and mechanical flexibility, provide an ideal functional platform for wearable electronic devices. Nevertheless, the development of NF-based wearable devices remains constrained by persistent bottlenecks in structural fabrication precision, material system selection, and practical application compatibility. Herein, this review systematically surveys the frontier research progress in electrospun NF-based wearable electronics. The design strategies and fabrication methodologies for diverse NF microarchitectures, including core-shell, porous, hollow, beaded, ribbon-shaped, and Janus asymmetric structures, are first introduced, followed by a systematic overview of key electrospinning technologies encompassing coaxial, aligned, yarn, and roll-to-roll scalable electrospinning processes. The frontier applications of conductive NF composites in physiological sensing, biological signal detection, triboelectric nanogenerators (TENG), human–machine interaction, electrochemistry and energy storage and textile-integration are then thoroughly examined. Building upon this foundation, the key challenges confronting the field are critically analyzed across three dimensions: material structural design, integrated fabrication processes, and bio-interface compatibility. Finally, future development directions are envisioned, encompassing machine learning-assisted design, robotics-enabled electrospinning, and big data-driven performance optimization, with the aim of providing theoretical guidance and technical reference for the rational design of next-generation high-performance NF-based wearable electronic devices.

Keywords: nanofibers; electrospinning; wearable electronics; bio-signal sensing; system integration

1. Introduction

Wearable electronic devices, serving as the core sensing interface between the human body and the digital world, have emerged as one of the most dynamic frontiers in contemporary flexible electronics research [1–7]. With the deep convergence of the Internet of Things (IoT), artificial intelligence (AI), and precision medicine, intelligent sensing systems capable of real-time, continuous, and non-invasive monitoring of human physiological states are facing unprecedented development opportunities alongside formidable technical challenges [8,9]. Recent advances in hybrid multimodal wearable sensors [10] and AI-assisted physiological monitoring [11] are accelerating the transition of wearable devices from laboratory prototypes to practical digital-health tools [12].



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In recent years, the global wearable medical device market has grown rapidly, with projections indicating that it will surpass the hundred-billion-dollar threshold by 2030, a market-driven imperative that has rendered the demand for high-performance, high-comfort, and highly reliable wearable sensing platforms increasingly acute [13]. However, conventional rigid electronic devices, owing to their inherent mechanical incompatibility, are ill-suited to establishing stable, conformal interfaces with the curvilinear surfaces of human skin. During prolonged wear, such rigid devices inevitably give rise to skin irritation, signal distortion, and device fatigue failure, thereby severely constraining their extension into wearable application scenarios [14]. To overcome this fundamental limitation, researchers have developed a range of strategies for constructing flexible electronic devices, including epidermal electronics based on ultrathin silicon-based micro/nanostructures [15] stretchable conductive networks based on elastomeric substrates [10,16] and intrinsically flexible transistor arrays based on organic semiconductor [17,18] and gas-permeable nanomesh electronics that mitigate skin inflammation [19,20]. Although these approaches have achieved notable breakthroughs in specific application contexts, they generally involve trade-offs among breathability, stretchability, sensing sensitivity, and manufacturability; consequently, how to reconcile high device performance with a high degree of mechanical compatibility with human skin remains the central scientific challenge confronting this field.

Against this backdrop, nanofibrous materials offer a breakthrough solution for constructing next-generation, high-performance wearable electronic devices, owing to their unique multidimensional structural advantages. Among various fabrication approaches, electrospinning has attracted particular attention [21–23]. It combines process simplicity, broad material versatility, and scalability potential, and its fundamentals, materials, and applications have been extensively reviewed [24–26].

Relative to conventional thin-film devices, electrospun NFs possess the following intrinsic merits: (i) an ultrahigh specific surface area ($100\text{--}1000\text{ m}^2/\text{g}$), which affords abundant anchoring sites for conductive functional fillers and effectively suppresses their agglomeration and detachment during dynamic deformation [27]; (ii) tunable fiber diameters (ranging from tens of nanometers to several micrometers) together with highly controllable microscale morphology, endowing fibrous membranes with cross-scale structural design freedom spanning from the nanoscale to the macroscale [28]; (iii) a naturally porous, breathable architecture (porosity $> 70\%$), which not only ensures skin comfort during long-term wear but also provides efficient pathways for sweat management and gas exchange, enabling breathable, waterproof, and washable device operation [29]; and (iv) excellent mechanical compliance and elastic recovery, enabling high-fidelity conformal contact with the skin and ensuring stable force-to-electrical signal transduction during motion [30]. These attributes have recently been exploited in NF-based strain sensors with synergistic conductive networks [31], all-NF TENGs for simultaneous energy harvesting and self-powered sensing [32], and oriented NF systems for multimodal sensing and gesture recognition [33].

The complete developmental trajectory of electrospinning-based wearable electronic devices, spanning foundational technological exploration (1995–2010) to application-driven rapid expansion (2013–present), is illustrated in Figure 1. In 1995, Doshi and Reneker systematically elucidated the complete electrospinning process, establishing a multidimensional regulatory framework encompassing solution properties, electric field parameters, and environmental conditions, thereby laying the experimental and theoretical foundation for modern electrospinning technology [34]. In 1996, Reneker and Chun demonstrated that more than twenty polymers could be electrospun into nanoscale ultrafine fibers, formally inaugurating the modern era of research into the large-scale application of NFs [35].

Entering the twenty-first century, four landmark achievements collectively propelled this field through a historic transition from mere NF fabrication toward the realization of functionalized flexible devices: (i) the development of carbon-nanotube-composite electrospun fibers in the early 2000s [36]; (ii) the first report of piezoelectric nanogenerators based on PVDF NFs (2008–2010) [37]; (iii) the proposal of the PVDF piezoelectric NF in 2013 [38]; and (iv) concentrated breakthroughs in high-performance flexible sensors based on MXene-composite NFs after 2018 [39]. Over the past five years, the successive emergence of milestone achievements such as helical continuous-fiber integrated circuits and fiber-based intelligent neural interfaces has marked the formal entry of electrospun-NF-based wearable electronics into a new stage of systems integration and clinical translation research.

Electrospinning technology combines excellent material compatibility with structural designability, enabling the controllable fabrication of NFs from polymers [40,41], metal oxides [42], carbon-based nanomaterials [43], and diverse composite material systems, and has thereby become a core platform technology for constructing high-performance functional materials [44]. Recent developments such as dynamic electrospinning of multi-material NF architectures further expand the attainable design space for programmable, multifunctional devices [45]. Through the regulation of polymer molecular architecture and spinning formulations, the mechanical, thermal, and chemical properties of the resulting fibers can be optimized [46]. Meanwhile, polymer-precursor-based systems permit the construction of diverse microstructures, including porous [47], core-shell [48], hollow [49], cross-linked [50], and composite architectures, effectively overcoming the performance limitations inherent to single-

phase fibers and substantially broadening the application scope of NFs in catalysis [51], energy [52], environmental remediation [40], and sensing [53]. In contrast to pure polymer fibers, metal oxide NFs can be prepared via precursor doping combined with high-temperature calcination: metal precursors are uniformly incorporated into the spinning solution prior to fiber formation, and subsequent high-temperature calcination removes the polymer template, yielding metal oxide NFs with regular architecture and superior thermal stability and mechanical properties, affording pronounced application advantages under harsh operating conditions such as elevated temperatures [54], catalytic environments [55], and strongly corrosive media [56]. By tuning the composition of the spinning solution, precursor concentration, and doping system, and by coupling these with post-processing treatments such as calcination, cross-linking, and etching, precise control can be exerted over fiber microscale morphology, pore structure, and phase-interface characteristics, thereby achieving performance complementarity across distinct material systems [57], compensating for the functional shortcomings of single-component fibers, and providing reliable technical options for the controllable design and industrial application of high-performance, multifunctional NF composites.

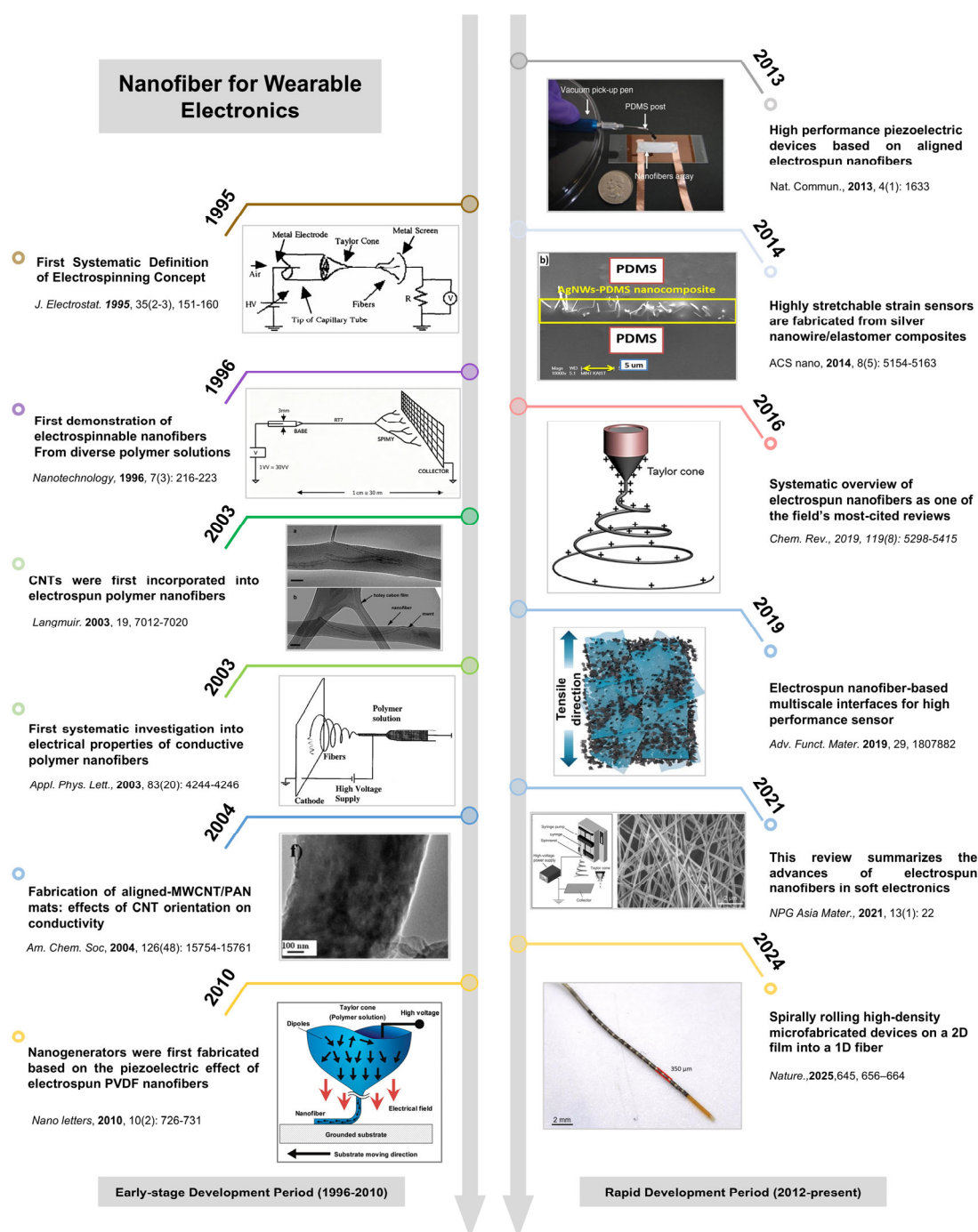


Figure 1. Timeline illustrating the evolution of electrospun NFs for wearable electronics. 1995, Electrospinning original conceptual diagram (first systematic definition of electrospinning), Reproduced with permission [34].

Copyright 1995, Elsevier. 1996, Schematic for the first fabrication of electrospun NFs from diverse polymer precursors, Reproduced with permission [35]. Copyright 1996, IOP Publishing. 2003, TEM visualization of carbon nanotubes (CNTs) embedded into electrospun polymer NF for the first time, Reproduced with permission [36]. Copyright 2003, American Chemical Society. 2003, Experimental setup for systematic characterization of conductive NF electrical properties, Reproduced with permission [58]. Copyright 2003, American Institute of Physics. 2004, Morphology of aligned MWCNT/polyacrylonitrile (PAN) NF mats investigating orientation-regulated conductivity, Reproduced with permission [59]. Copyright 2004, American Chemical Society. 2010, Schematic of PVDF electrospun NF-based piezoelectric nanogenerators, Reproduced with permission [60]. Copyright 2010, American Chemical Society. 2013, High performance PVDF piezoelectric NF, Reproduced with permission [38]. Copyright 2013, Springer Nature. 2014, Cross-section micrograph of stretchable silver nanowire composite strain sensors, Reproduced with permission [61]. Copyright 2014, American Chemical Society. 2016, Electrospinning illustration from a top-cited comprehensive review of NF technology, Reproduced with permission [62]. Copyright 2016, American Chemical Society. 2019, NF multiscale composite structure for high-sensitivity wearable sensing, Reproduced with permission [63]. Copyright 2019, Wiley-VCH GmbH. 2021, Schematic summary of electrospun NF advances in soft wearable electronics, Reproduced with permission [39]. Copyright 2021, Springer Nature. 2024, Optical image of spiral-rolled 1D functional fibers transformed from 2D microfabricated thin films, Reproduced with permission [64]. Copyright 2024, Springer Nature.

Despite the staged progress achieved in NF-based wearable electronics, this field continues to confront several critical technical bottlenecks awaiting resolution [65]. The first concerns the challenge of synergistic multifunctional integration: achieving sensing, energy harvesting, and signal processing simultaneously within a single fibrous system, while circumventing mechanical interference and signal crosstalk among functional modules, remains a central challenge in wearable device design. The second pertains to insufficient stability in large-scale fabrication: the electrospinning process is highly sensitive to environmental humidity, solution viscosity, and other parameters, such that laboratory-scale refined protocols are difficult to directly translate to continuous industrial production, and batch-to-batch inconsistencies in fiber morphology and performance severely constrain commercialization [66]. The third involves the poor long-term stability of biological interfaces: the acidic-to-alkaline skin environment, together with chloride ions and organic metabolites present in sweat, corrodes conductive functional fillers, while sustained mechanical friction progressively weakens the interfacial adhesion between fiber and skin, substantially compromising the long-term service reliability of the device [67]. The fourth relates to the considerable difficulty of decoupling multimodal signals: temperature, pressure, humidity, and other physical quantities exhibit pronounced cross-interference, such that a single sensing mechanism is inadequate for the precise, independent detection of multiple parameters.

In recent years, several reviews have summarized electrospun NFs from different perspectives. Cho et al. adopted a process-oriented view, systematically covering the fundamentals of electrospinning, the fabrication of porous, core-shell, hollow, and aligned NFs, and advanced techniques such as coaxial, yarn, and roll-to-roll electrospinning, and identified AI-assisted optimization and robotic electrospinning as key routes to scale-up [68]. However, the applications they cover focus mainly on functional membranes, sensing, energy, and catalysis, and wearable electronics represents only a small part of the discussion. Zhang et al. focused on wet electrospinning, discussing improvements in equipment and its potential for morphology control [69]; this is again a process-level summary, and a gap remains between it and the functional requirements of wearable devices. Teng et al. directly targeted intelligent wearables, describing engineered NFs in health monitoring, biotherapy, and smart textiles, and emphasizing the integration of functional devices into fabrics to balance performance and comfort [70]. Nevertheless, their discussion is organized mainly by application scenario, and offers limited insight into how fiber structure determines sensing performance, or into bottlenecks such as scalable fabrication and biointerface stability.

To address these limitations, this review starts from jet dynamics and processing parameters, clarifies how they govern NF microstructure, and then summarizes construction strategies for core-shell, hollow, and porous architectures. On this basis, polymer-, MXene-, CNT-, and multicomponent hybrid-based conductive systems are compared in terms of network construction and its influence on sensing performance, thereby establishing an explicit link between fiber structure and device performance. We then systematically examine how these designs are realized in practical devices, including textile-integrated sensing, physiological signal monitoring, triboelectric nanogenerators, and human-machine interaction. Finally, in view of the bottlenecks outlined above, we analyze the core challenges from the perspectives of material design, process integration, and biointerface optimization and, in conjunction with artificial intelligence and robotic manufacturing, discuss future development directions.

2. Electrospinning Technology

2.1. Fundamental Principles and Mechanisms

Electrospinning is an electrohydrodynamic processing technique that employs a high-voltage electrostatic field to draw polymer solutions or melts into ultrafine fibers, its underlying essence being a process of polymer jet stretching and thinning driven by electrostatic forces. A typical apparatus comprises a high-voltage power supply, a spinneret, a collector, and a solution reservoir unit (Figure 2a). Figure 2b intuitively depicts the microscale fluid evolution governing the entire electrospinning process. In contrast to conventional single-needle spinning, which is limited by its inherent drawback of generating only a single jet and thus suffers from low production efficiency, rotating-disk-assisted spinning enables the simultaneous generation of multiple jets at the disk edge, thereby enhancing throughput; moreover, the synergistic stretching effect of centrifugal force and electric field force effectively refines the fibers and narrows the diameter distribution, markedly improving the uniformity of fiber formation and overall fabrication quality (Figure 2c).

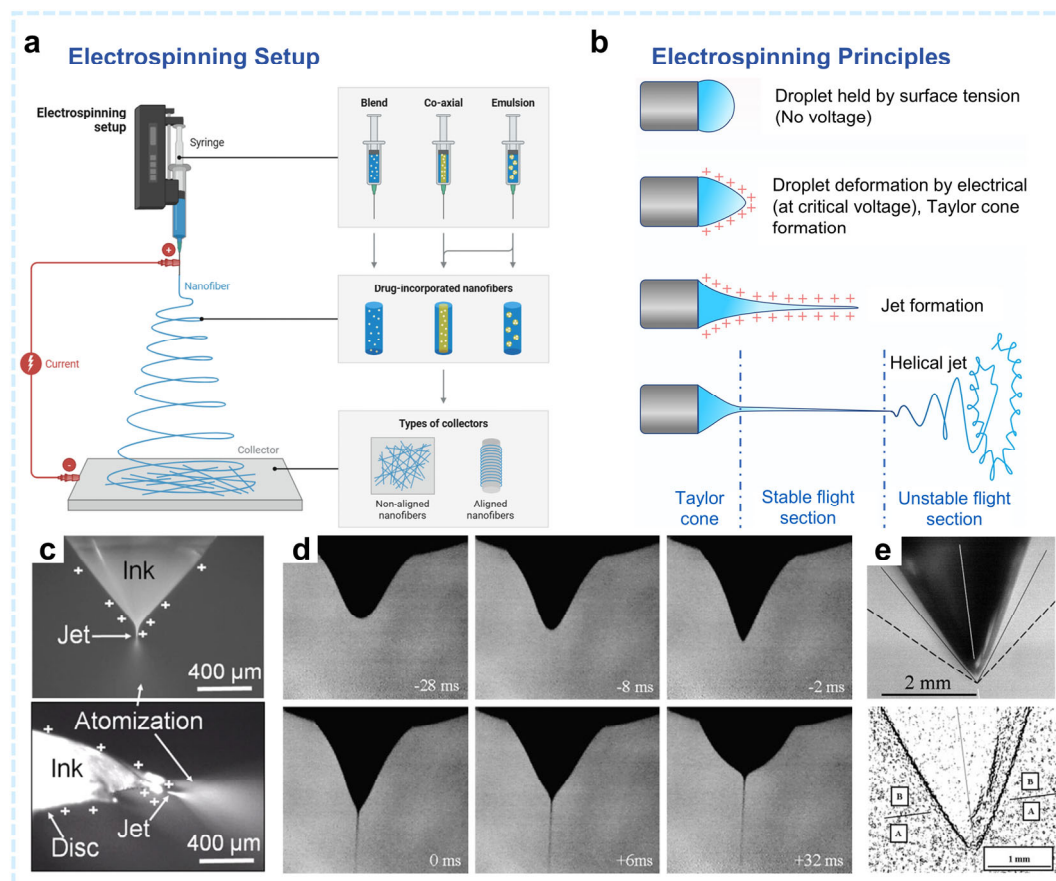


Figure 2. Schematic illustration of the electrospinning principle and representative SEM morphologies of the resulting NF architectures. (a) Electrospinning apparatus and representative NF structures obtained from different spinning solutions and collector configurations. (b) Schematic diagram of the fiber formation mechanism during electrospinning. Reproduced with permission [71]. Copyright 2024, Cell Press. (c) Optical photographs of the Taylor cone, jet and atomized droplets generated from a positively charged nozzle and conductive tips. Reproduced with permission [72]. Copyright 2023, Springer Nature. (d) Sequential dynamic images showing the temporal evolution of Taylor cone formation and jet development. Reproduced with permission [73]. Copyright 2008, Elsevier. (e) Macroscopic morphology of the Taylor cone and microscopic zonation of the cone surface. Reproduced with permission [73]. Copyright 2008, Elsevier.

Under a conventional high-voltage electrostatic field of 10–30 kV, the polymer droplet at the spinneret tip undergoes progressive morphological reshaping owing to the dynamic interplay between electric field forces and surface tension: in the absence of an applied field, the droplet retains a spherical shape under the influence of surface tension alone; once the voltage is increased beyond a critical threshold, the electric field acting at the liquid–air interface drives the droplet to deform into a Taylor cone, a structure first proposed on the basis of hydrostatic theory and subsequently validated experimentally by G. I. Taylor between 1964 and 1969 (Figure 2d–e) [72,73]. As the

applied voltage continues to increase, a localized electric field maximum develops at the apex of the Taylor cone, prompting the polymer liquid to overcome interfacial confinement and eject as a continuous charged jet, which initially maintains a stable, straight-line trajectory. The jet subsequently enters a region of instability, undergoing whipping motion induced by bending instability, during which it is substantially stretched and thinned, its diameter reduced by one to three orders of magnitude, thereby accomplishing the transition from the micrometer to the nanometer scale. Concurrently, rapid solvent evaporation and orientational solidification of the polymer molecular chains occur, ultimately yielding solidified ultrafine NFs that are deposited in an ordered manner onto the grounded collector surface and accumulate into a nonwoven nanofibrous membrane possessing a porous network architecture. The resulting fibrous membrane exhibits excellent interconnected porosity and a high specific surface area, thereby providing abundant loading sites and mass-transport pathways for functional modification in sensing, filtration, adsorption, and related applications.

2.2. Processing and Material Parameters of Electrospinning

During the electrospinning process, the morphology, structure, and ultimate properties of NFs are governed by the highly coupled interplay of multiple process variables, including electric field conditions, solution properties, collector configuration, and environmental parameters (Table 1), systematic regulation of these spinning parameters constitutes the core prerequisite for achieving controlled NF fabrication. First, with respect to electric field parameters, a moderate increase in applied voltage enhances jet stretching and reduces fiber diameter; however, excessively high voltages cause the jet to solidify before reaching the collector, thereby shortening the unstable whipping region and, counterintuitively, increasing fiber diameter. Conversely, if the field strength is insufficient, the electric traction force fails to stably sustain the equilibrium conformation of the Taylor cone, resulting in disordered cone-surface deformation and inadequate jet stretching and breakup, ultimately yielding fibers with uneven thickness and poor morphological consistency [74]. Another critical parameter is the flow rate of the electrospinning solution. The feed rate of the syringe pump must be precisely matched to the solvent evaporation rate: an excessively high flow rate results in insufficient solvent evaporation during flight, such that residual solvent remains upon the fiber's arrival at the collector, whereas an excessively low flow rate causes intermittent jet supply and destabilizes the spinning process. The spinning flow rate must therefore be precisely matched to the solvent evaporation rate to ensure stable spinning [75]. Working distance, defined as the vertical spacing between the spinneret and the collector plate, likewise constitutes a core parameter governing fiber formation. The collection distance must be adapted to the solvent evaporation efficiency. An excessively short distance provides insufficient time for solvent evaporation, causing the fibers to adhere and agglomerate, whereas an excessively long distance attenuates the field strength, diminishing the jet's stretching capacity and resulting in fibers of uneven thickness. These spinning factors must therefore be carefully considered and optimized in concert to ensure structural consistency of the resulting NFs [76].

Table 1. Influence of electrospinning parameters on NF morphology, structure, and properties.

Parameter ↑	Morphological Effect	Structural Effect	Property Effect	Optimization Strategy
Solution concentration	Diameter ↑ beads ↓	Chain entanglement ↑	Strength ↑	Select concentration above critical entanglement threshold
Applied voltage	Diameter ↓ then ↑	Jet stretching ↑	Uniformity optimized ↑	Maintain moderate voltage range
Flow rate	Diameter ↑	Solvent evaporation ↓	Defect density ↑	Match flow rate with evaporation rate
Collector speed	Alignment ↑	Orientation ↑	Mechanical performance ↑	Use a high-speed rotating collector
Humidity	Porosity ↑	Crystallinity altered	Surface area ↑	Control relative humidity

↑ means increase; ↓ means decrease.

To fabricate NFs with uniform morphology and well-developed structure, the various parameters of the spinning dope must be regulated in tandem. Among these, polymer concentration governs the degree of molecular chain entanglement and directly determines fiber diameter and microscale morphology, below the critical entanglement concentration, insufficient chain entanglement causes the jet to fragment under electrostatic force, forming beaded, defect-laden fibers; at moderate concentrations, sufficiently entangled polymer chains confer adequate viscoelasticity on the jet to resist breakup, yielding continuous, uniform fibers; whereas at excessively high concentrations, the markedly elevated solution viscosity precludes the formation of a stable Taylor cone or even renders spinning altogether infeasible [77]. The evaporation rate, dielectric constant, and surface tension of the solvent system collectively determine the solvent evaporation rate and solidification timing of the jet during flight, thereby

influencing the pore structure and surface morphology of the resulting fibers [78]. Highly volatile solvents enable solidification within a short flight distance but may also cause premature solvent evaporation at the spinneret tip, leading to solute precipitation and clogging of the spinning orifice; conversely, low-volatility solvents evaporate more slowly, such that substantial residual solvent remains when the fibers reach the collecting substrate, readily giving rise to defects such as fiber adhesion and pore collapse within the membrane layer [79]. A higher dielectric constant enhances the charge-carrying capacity of the solution, thereby reinforcing the electric field's stretching and thinning effect on the jet, whereas excessively high surface tension impedes the stable formation of the Taylor cone, favoring droplet formation over continuous fiber generation. In practical spinning processes, these three solvent characteristics must therefore be judiciously balanced to obtain NFs of superior morphology. Systematic optimization of these spinning-dope parameters enables the fabrication of NFs with regular structure and uniform morphology.

Collector configuration and environmental variables likewise regulate the formation characteristics of NFs across multiple dimensions. High-speed rotating-drum collectors (rotational speed > 1000 rpm) can induce a high degree of fiber alignment through mechanical drawing action, and the resulting aligned fibrous membranes exhibit pronounced anisotropy, with tensile strength along the direction parallel to fiber alignment reaching 2–5 times that measured in the perpendicular direction, providing an ideal structural substrate for constructing anisotropic flexible strain sensors [80]. Among environmental variables, ambient relative humidity exerts a particularly pronounced regulatory effect on the microscale pore structure of the fibers: under high-humidity conditions (relative humidity > 60% RH), water vapor condenses on the surface of the nascent jet, inducing ternary phase separation among polymer, solvent, and water, which can generate a regular honeycomb-like porous structure on the fiber surface; such high-specific-surface-area porous fibers offer distinctive application advantages in chemical sensing scenarios [81]. Temperature, in turn, regulates the fiber solidification process by altering the solvent evaporation rate: elevated temperatures accelerate solvent evaporation and shorten the jet solidification time, effectively suppressing inter-fiber adhesion; however, excessively high temperatures can induce overly rapid solvent evaporation, giving rise to surface defects such as pores and brittle fracture. Under low-temperature conditions, by contrast, the solvent evaporation rate is markedly slowed and jet solidification is delayed, such that incompletely removed residual solvent readily causes adjacent fibers to adhere to one another upon deposition, compromising the uniformity of the membrane layer [82]. Environmental factors therefore play a pivotal role in determining both the morphological consistency of NFs and the reproducibility of experimental outcomes.

2.3. Microstructures of Electrospun NFs

By judiciously tailoring the spinning-dope formulation, spinneret architecture, and collection modality, electrospinning enables the precise construction of a diverse array of functional NF morphologies, ranging from simple homogeneous fibers to complex, multilevel hierarchical architectures. This capacity for microstructural design far exceeds that afforded by conventional melt- or solution-spinning processes and constitutes the fundamental basis for the irreplaceable status of electrospinning within the field of wearable electronic devices.

Core-shell NFs consist of a polymeric core enveloped by an outer sheath layer; this bilayer architecture not only enhances the mechanical properties of the fiber but also confers diverse functionalities unattainable in single-layer fibers, rendering it one of the most extensively investigated and highly functionalized composite fiber structures to date [48,83]. Core-shell NFs can be directly formed via a one-step coaxial electrospinning process, thereby circumventing the need for multiple complex post-processing steps and substantially reducing fabrication complexity [84]. For instance, Meng et al. fabricated a core-shell nanofibrous thermo-moisture regulating textile via coaxial electrospinning (Figure 3a) [85], in which a PU/PEG phase-change composite system was injected into the inner channel of a coaxial spinneret to form the fiber core, while a mixed solution of PU loaded with high-specific-surface-area activated carbon (AC) served as the outer sheath. Under the applied high-voltage field, the two-phase jet underwent synchronous stretching and solidification, yielding a sheath-core microstructure with a well-defined interface and complete phase separation. The temperature gradient established between the sheath and core drives a phase-change effect that confers active thermal-management capability upon the fiber: the sheath-layer PU/PEG phase-change material undergoes a solid-liquid transition near 37 °C, absorbing metabolic heat dissipated from the skin, while the core-layer PU/AC framework provides the requisite mechanical support, preventing leakage of the molten phase-change material from the fiber. Benefiting from the synergistic action of a three-tier heat-dissipation mechanism—phase-change heat storage, moisture evaporation, and infrared radiative cooling—this textile achieves a mid-infrared emissivity of 99.82% and a contact cooling coefficient of 0.43 W cm⁻², reduces skin temperature by 6.6 °C under a 40 °C high-temperature environment, and exhibits high-precision humidity responsiveness down to 0.5% RH. This functionally and structurally partitioned core-shell design paradigm provides a highly extensible structural template for constructing multifunctional fibers that integrate sensing, thermal management, and mechanical support within a single system.

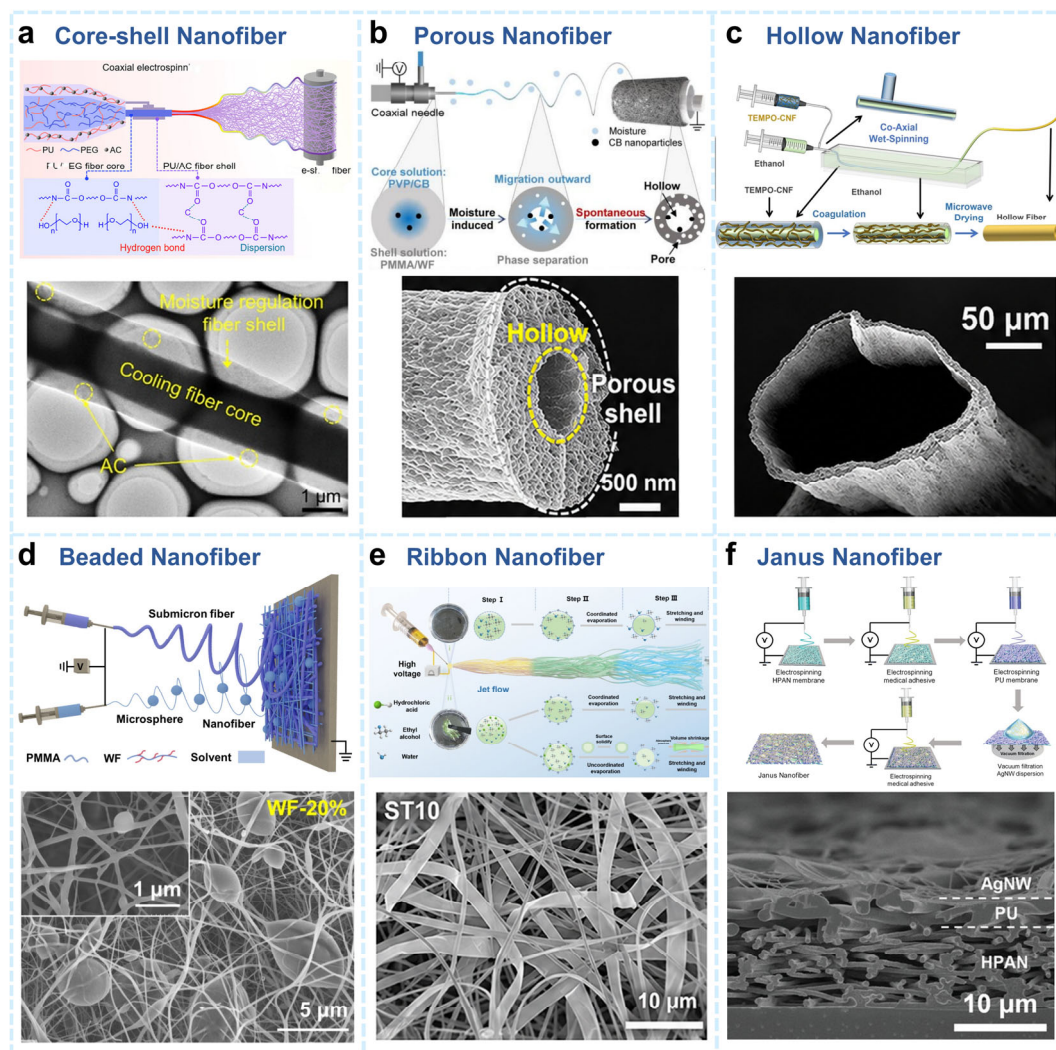


Figure 3. Schematic diagrams of mainstream electrospun NF structures and corresponding SEM morphology images. **(a)** Core-shell structure. Reproduced with permission [85]. Copyright 2026, Wiley-VCH GmbH. **(b)** Porous structure. Reproduced with permission [86]. Copyright 2026, Elsevier. **(c)** Hollow structure. Reproduced with permission [87]. Copyright 2023, American Chemical Society. **(d)** Bead structure. Reproduced with permission [88]. Copyright 2025, Elsevier. **(e)** Ribbon structure. Reproduced with permission [89]. Copyright 2025, Springer Nature. **(f)** Janus structure. Reproduced with permission [90]. Copyright 2022, Wiley-VCH GmbH.

Porous NFs are nanofibrous materials possessing continuous, interconnected micropores distributed throughout the fiber body or surface layer; the pore channels constructed within the fiber substantially increase the specific surface area, providing abundant active sites, extensive internal space, and heterogeneous interfaces that effectively accelerate mass diffusion, transport, and conversion processes [91,92]. Two principal approaches dominate the fabrication of such fibers: phase separation and template-assisted etching. The phase-separation method relies on in situ pore formation driven by solvent diffusion during the spinning process, whereas the template-assisted approach first co-electro spins a sacrificial template with the polymer, followed by subsequent template removal to yield the porous structure, an operationally simple and broadly applicable strategy [93]. For example, Chen et al. employed a PMMA/aramid-NF (WF) blend solution as the spinning feedstock (Figure 3b) [86], and exploiting a controlled phase-separation mechanism induced by PVB/NC phase separation and formic acid treatment, formed a porous shell layer on the PMMA fiber surface with an average pore diameter of approximately 200 nm and a porosity exceeding 60%, while the WF component formed an interpenetrating network throughout the fiber, providing additional mechanical reinforcement. The introduction of this porous architecture increased the fiber specific surface area by an order of magnitude (from $\sim 15 \text{ m}^2/\text{g}$ to $\sim 150 \text{ m}^2/\text{g}$), markedly increasing the density of effective anchoring sites for conductive fillers and, in chemical sensing applications, enhancing the adsorption–desorption kinetics of gas molecules to achieve faster sensing response and a lower detection limit.

Hollow NFs are NFs possessing an internal, continuous tubular lumen; this hollow channel substantially reduces the bending stiffness of the material and establishes an axially continuous mass-transport pathway,

conferring distinctive advantages in pressure sensing and biochemical detection [94,95]. This structure is primarily fabricated via coaxial electrospinning combined with post-spinning etching: a dual-fluid coaxial spinneret is first employed to co-extrude core- and sheath-phase spinning solutions, forming a composite fiber, after which the sacrificial core layer is selectively dissolved away, ultimately yielding an intact hollow tubular structure [96]. For instance, Niu et al. employed an aqueous dispersion of TEMPO-oxidized cellulose NFs (TEMPO-CNF) as the core fluid and a PVDF/carbon-black (CB) nanoparticle composite solution as the sheath spinning solution (Figure 3c) [87]; following coaxial spinning, the CNF core layer was removed by ethanol-immersion etching, yielding hollow PVDF/CB composite NFs with a uniform wall thickness (~100 nm) and an open, permeable lumen. This precisely engineered hollow lumen confers a markedly reduced bending stiffness together with distinctive axial capillary mass-transport capability: in pressure-sensing applications, the hollow fiber exhibits heightened structural sensitivity to weak pressure stimuli owing to its lower bending stiffness, while the hollow lumen can simultaneously function as a microchannel to guide the directional transport of sweat, providing a natural microfluidic interface for in situ biochemical sensing.

Beaded NFs constitute a “microsphere–fiber–microsphere” dumbbell-shaped hierarchical material formed by ultrafine fibers interconnecting submicron microsphere nodes, this morphology arises spontaneously from jet instability in low-viscosity spinning solutions and can be fabricated by reducing polymer concentration and modulating spinning voltage and solution surface tension [97,98]. Chen et al. blended a silicone-modified PU water-repellent agent with PMMA within a PU matrix, precisely fabricating a regular beaded structure under low-concentration spinning conditions (Figure 3d) [88]. This hierarchical architecture exhibits a two-stage nonlinear force–electrical response, under low compressive strain, only the ultrafine fibrous skeleton bends, resulting in gradual resistance change; once strain exceeds a threshold, the microsphere nodes come into mutual contact, causing a sharp increase in conductive pathways and an abrupt stepwise change in resistance. The interweaving of microspheres with the dual-scale fibrous network forms a highly roughened, porous structure that confers excellent water-repellent and breathable properties on the material, broadening its application potential in athletic and medical protective textiles.

Ribbon-shaped NFs are NFs possessing a flattened, elongated cross-section, distinct from the conventional circular geometry, two principal fabrication strategies currently prevail: high-speed drum collection, which induces flattening of the jet, and modulation of the spinning solution’s evaporation rate to induce collapse of the nascent fiber’s cross-section, fiber aspect ratio can be conveniently tuned by adjusting collection conditions and solution viscoelasticity [99,100]. For example, Cheng et al. employed a high-speed drum-collection strategy, increasing the collecting-drum rotational speed to above 2000 rpm and matching the viscoelastic parameters of the spinning solution to induce flattening collapse of the circular jet prior to solidification, thereby producing regular ribbon-shaped NFs with an aspect ratio of 5–10 (Figure 3e) [89]. This flattened cross-section confers a dual structural advantage: at equivalent fiber loading, ribbon-shaped fibers increase the in-plane conductive contact area by a factor of three, enhancing the connectivity of the conductive network, while the flattened geometry substantially reduces the transverse bending stiffness of the fiber, endowing the resulting membrane with excellent conformability to curved surfaces, rendering it particularly well suited for skin-conformal flexible sensing applications.

Janus NFs are differentiated composite fibers possessing asymmetric bifacial chemical compositions, enabling multifunctional zonal integration through the contrasting physicochemical properties of their two interfacial sides, and represent a structural motif of considerable recent interest in the field of multifunctional textile sensing [101,102]. Side-by-side dual-fluid co-spinning constitutes the predominant strategy for fabricating Janus fibers, enabling hydrophilic and hydrophobic functional components to be respectively loaded onto the two sides of a single fiber cross-section, thereby precisely constructing an asymmetric bifacial interface. For example, Yang et al. employed synchronous side-by-side dual-nozzle electrospinning to co-form a hydrophilic modified polyacrylonitrile (HPAN) solution and a hydrophobic PU solution doped with silver nanowires (AgNWs), yielding a bifacial Janus fibrous membrane with a hydrophilic HPAN side and a hydrophobic PU-AgNWs side (Figure 3f) [90]. The differential wettability between the two fiber surfaces establishes a directional capillary pressure gradient that drives unidirectional transport of sweat from the hydrophobic skin-facing side outward to the hydrophilic outer surface, thereby preventing sweat retention against the skin; simultaneously, the AgNWs distributed within the hydrophobic layer form a continuous conductive network whose effective conductive cross-sectional area varies dynamically with ambient humidity, generating an electrical output signal that correlates with the sweat rate. This asymmetric architecture achieves the integration of unidirectional sweat management with in situ humidity sensing, conferring distinctive advantages for wearable textiles designed for human sweat monitoring.

2.4. Advanced Electrospinning Technologies

2.4.1. Co-Electrospinning

Co-electrospinning enables the synergistic fiber formation of multiple spinning solutions, allowing the spatial distribution and structural control of different components within a single NF. Among these approaches, coaxial electrospinning employs nested spinnerets to construct core-shell or multilayer architectures. This integrates the functions of the individual components while protecting active species and enabling their controlled release, offering an effective route to multifunctional NFs [103–105]. However, the technique places stringent demands on the rheological properties, component compatibility, and flow-rate matching of the spinning solutions, and interfacial instability may give rise to structural defects [106]. The complex spinneret design and process control further hinder scale-up. To meet the functional-integration requirements of biomedical materials, Fang et al. fabricated ionic-gradient NFs via triaxial electrospinning, comprising a cationic core, a PVA intermediate layer, and an anionic CA outer layer (Figure 4a) [107]. The ionic polarity difference among the components generates an interfacial electrochemical response. Combined with the antibacterial activity of QCS and the protective, controlled-release function of the CA shell, this enables a synergistic design of hemostatic function and material structure. This work highlights the potential of coaxial electrospinning to regulate fiber interfacial functionality through the spatial positioning of components, while also indicating that practical applications must still balance structural stability with process controllability.

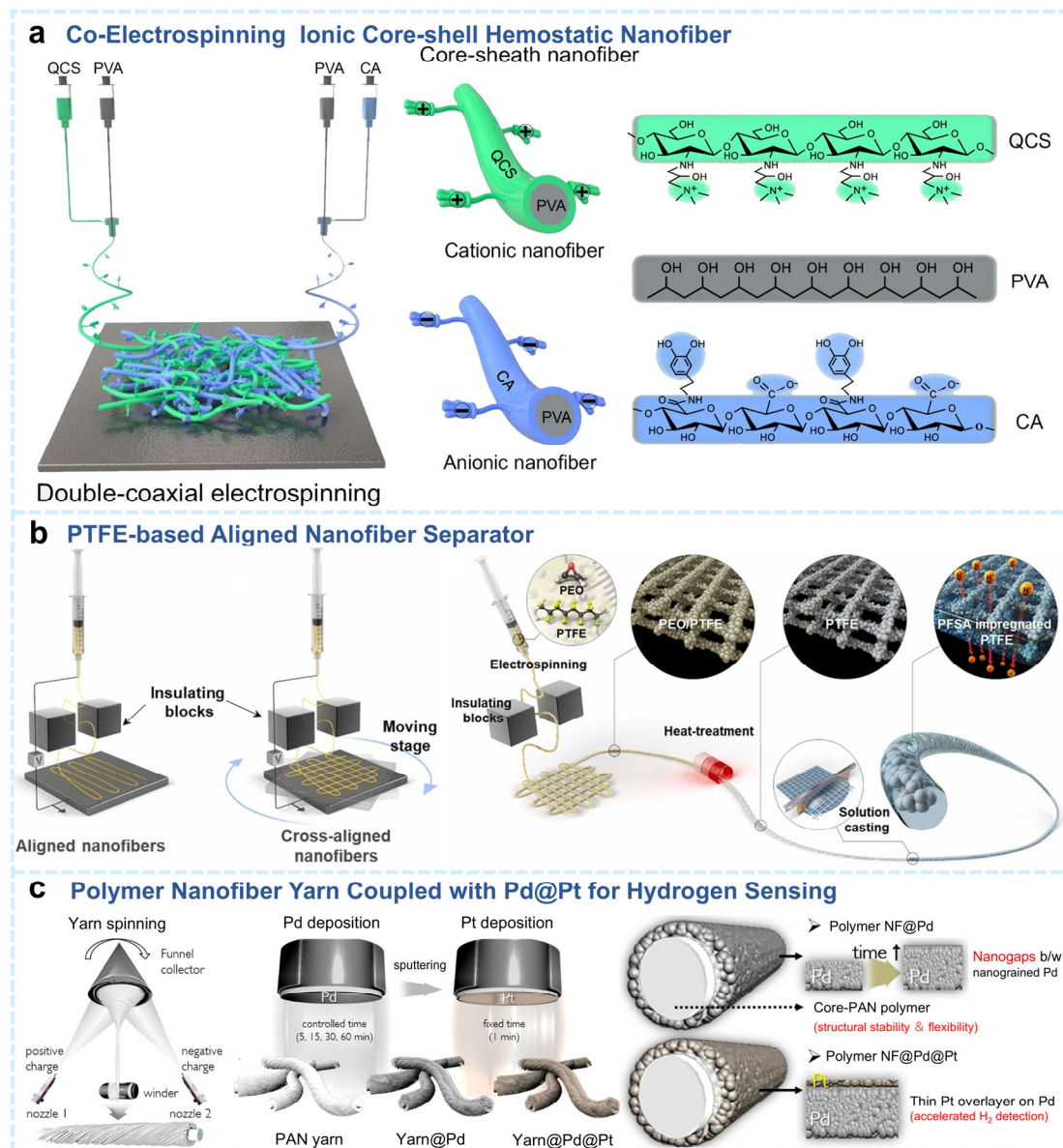


Figure 4. Schematic diagrams of advanced electrospinning technologies, including co-electrospinning, aligned electrospinning, and yarn electrospinning. (a) Co-electrospinning ionic core-shell hemostatic NF. Reproduced with

permission [107]. Copyright 2025, Springer Nature. (b) PTFE-based aligned NF separator. Reproduced with permission [108]. Copyright 2022, Elsevier. (c) Polymer NF yarn coupled with Pd@Pt for hydrogen sensing. Reproduced with permission [109]. Copyright 2019, American Chemical Society.

2.4.2. Aligned Electrospinning

Aligned electrospinning, through the coupling of external fields such as an auxiliary electric field or a mechanically driven force, achieves a highly ordered and directionally aligned arrangement of nanoscale units during the fiber-collection stage, yielding functional membranes with anisotropic structural characteristics and thereby providing the structural foundation for fabricating sensing devices with anisotropic architectures [110,111]. For example, Hwang et al. employed a polytetrafluoroethylene/poly(ethylene oxide) (PTFE/PEO) blend system (mass ratio 3:1) as the spinning precursor, coupling the transverse aligned electric field generated by interdigitated parallel electrodes with the mechanical drawing force imparted by a high-speed rotating drum to achieve synergistic collector-driven regulation, thereby successfully fabricating a highly ordered PTFE-based composite nanofibrous membrane with a degree of alignment as high as 0.95 (Figure 4b) [108]. Following high-temperature thermal treatment at 300 °C to selectively remove the sacrificial PEO phase, the resulting pure PTFE aligned nanofibrous membrane exhibited a fully fluorinated superhydrophobic interfacial character (water contact angle > 160°) together with pronounced anisotropic wetting behavior, with the liquid spreading rate along the fiber-alignment direction reaching 4.8 times that measured in the perpendicular direction, achieving precise, direction-selective control over wettability and providing a controllable structural design paradigm for constructing directional liquid-management devices and highly selective sensing membranes. This study elucidates the relationship between electrospun fiber alignment and functional anisotropy, providing core theoretical support for the integrated structure–property design of aligned functional membrane materials.

2.4.3. Yarn Electrospinning

Yarn electrospinning technology, through funnel-type rotating collection devices or liquid-bath-assisted collection strategies [112,113], enables the continuously deposited NF bundle to be real-time converged, twisted, and solidified into a continuous fibrous yarn, thereby overcoming the morphological limitation of conventional electrospun NFs membranes as “two-dimensional brittle films.” This endows NF-based functional materials with macroscale architecture and processability compatible with conventional textile systems, providing the fabrication foundation for the textile integration of flexible wearable electronic devices [114,115]. For example, Kim et al. employed PAN as the flexible skeletal matrix and high-purity palladium/platinum (Pd/Pt) bimetallic nanounits as the catalytically active sensing component, continuously fabricating PAN nanofibrous yarn via yarn electrospinning; on this basis, a Pd nanoscale conductive network was constructed via magnetron sputtering, followed by deposition of an ultrathin Pt protective layer, precisely yielding PAN composite nanofibrous yarn functionalized with Pd@Pt core–shell nanoparticles, which was successfully applied to high-performance hydrogen (H₂) sensing detection (Figure 4c) [109]. Benefiting from the distinctive morphological advantage of continuous macroscale yarn, this sensing unit can be directly woven and embedded into commercial textile substrates, achieving seamless integration of real-time H₂ sensing functionality with the flexibility, comfort, and breathability of wearable textiles; this study offers meaningful guidance for the practical application of wearable devices for H₂ safety monitoring.

2.4.4. Roll-to-Roll Electrospinning with Multi-Nozzle Technique

Roll-to-roll (R2R) multi-nozzle electrospinning constitutes the core engineering technology driving the transition of nanofibrous membrane fabrication from small-batch laboratory production to continuous, stable industrial-scale manufacturing, and serves as the key enabling support for the commercial implementation of this class of materials [116,117]. Relative to conventional single-nozzle electrospinning, the core technical advantages of the R2R multi-nozzle system manifest along three dimensions. First, with respect to production capacity, the linear or matrix arrangement of hundreds to thousands of nozzles can increase output per unit time by two to three orders of magnitude, achieving a leap from milligram-per-hour to kilogram-per-hour production scales. Second, with respect to web width, reliance on a continuously advancing flexible roll-to-roll collection substrate enables the fabrication of large-area fibrous membranes with widths of 1–4 m, rendering the process highly compatible with existing nonwoven fabrication equipment. Third, with respect to continuous manufacturing, the integration of solution supply, closed-loop tension control, and in-line defect detection enables uninterrupted deposition of the nanofibrous membrane together with automated roll-up [116]. For example, Zheng et al. combined roll-to-roll electrospinning with the fabrication of two-dimensional nanofibrous membranes, employing them as a medium to

construct a continuous twisting production line that achieves the scalable conversion of aerogel particles into macroscopic continuous yarn. The low-loading NF-twisted network provides stable structural support for a high-volume-fraction ($\approx 78\%$) aerogel particulate phase, fully preserving the porous thermal-insulation architecture; the resulting yarn combines high strength, high flexibility, and excellent thermal-insulation properties, with woven fabrics exhibiting superior warmth retention relative to cashmere and stable performance across a temperature range of -196 to 100 °C under conditions of repeated deformation and washing. This integrated R2R process offers a flexible and viable pathway toward scalable fabrication for extending aerogel textile materials through additional functional modifications such as dyeing, hydrophobic treatment, and Joule heating.

Despite its considerable potential for scale-up, R2R multi-nozzle electrospinning continues to confront several critical engineering challenges in the course of industrial implementation: electric-field interference among nozzles within the array readily induces jet deviation and nonuniform deposition; solvent evaporation causes real-time drift in spinning-solution viscosity, directly affecting process stability; and fluctuations in environmental parameters such as temperature and humidity exert a more pronounced influence on fiber morphological uniformity under large-scale production conditions. Systematic resolution of these challenges will continue to depend on in-line characterization, real-time feedback, and intelligent control technologies to advance R2R electrospinning equipment toward higher precision and greater stability.

2.5. Spinning Methods and Post-Processing Strategies for Hierarchically Structured NFs

By regulating spinneret configuration, the external field applied during fiber formation, the solidification medium, and high-temperature post-processing strategies, the microscale morphology and compositional architecture of NFs can be precisely controlled, enabling the construction of functionalized fibrous structures, including hollow, gel-based, and heterogeneous hierarchical architectures, adaptable to a wide range of material systems. This section examines three representative spinning fabrication processes, together with their corresponding landmark studies: coaxial electrospinning, wet-spinning coagulation, and electrospinning coupled with high-temperature modification. Drawing on the relevant literature, the formation mechanisms, fabrication procedures, and structural-regulation advantages of each process are discussed, elucidating the structure–property relationships among processing parameters, microscale architecture, and material functionality.

2.5.1. Coaxial Electrospinning

Coaxial electrospinning enables the co-ejection of core and sheath spinning solutions, constructing core-shell structures in a single-step fiber-forming process. Combined with sacrificial templating, heat treatment, or selective etching, it further allows the fabrication of hollow and multilayer fibers [118]. The technique permits control over component distribution, interfacial structure, and internal mass-transport channels, offering a versatile route to multifunctional composite fibers and functional hollow architectures [119]. However, the viscosity, miscibility, and flow-rate matching of the core and sheath fluids directly govern the integrity of the core-shell structure, and subsequent template removal and heat treatment may induce fiber shrinkage, defects, or structural damage, which complicates process control and scale-up. Liu et al. combined coaxial high-speed airflow-assisted drawing with a sacrificial core template, using polyamic acid as the sheath precursor and thermally decomposable silicone oil as the core, to prepare hollow polyimide NFs with continuous inner lumens (Figure 5a) [120]. This work demonstrates the feasibility of regulating the internal fiber structure through coaxial spinning coupled with post-treatment. Overall, the key advantage of coaxial electrospinning lies in the spatial distribution of multiple components and the designability of internal structures, yet its application remains constrained by fluid matching, post-treatment stability, and process complexity.

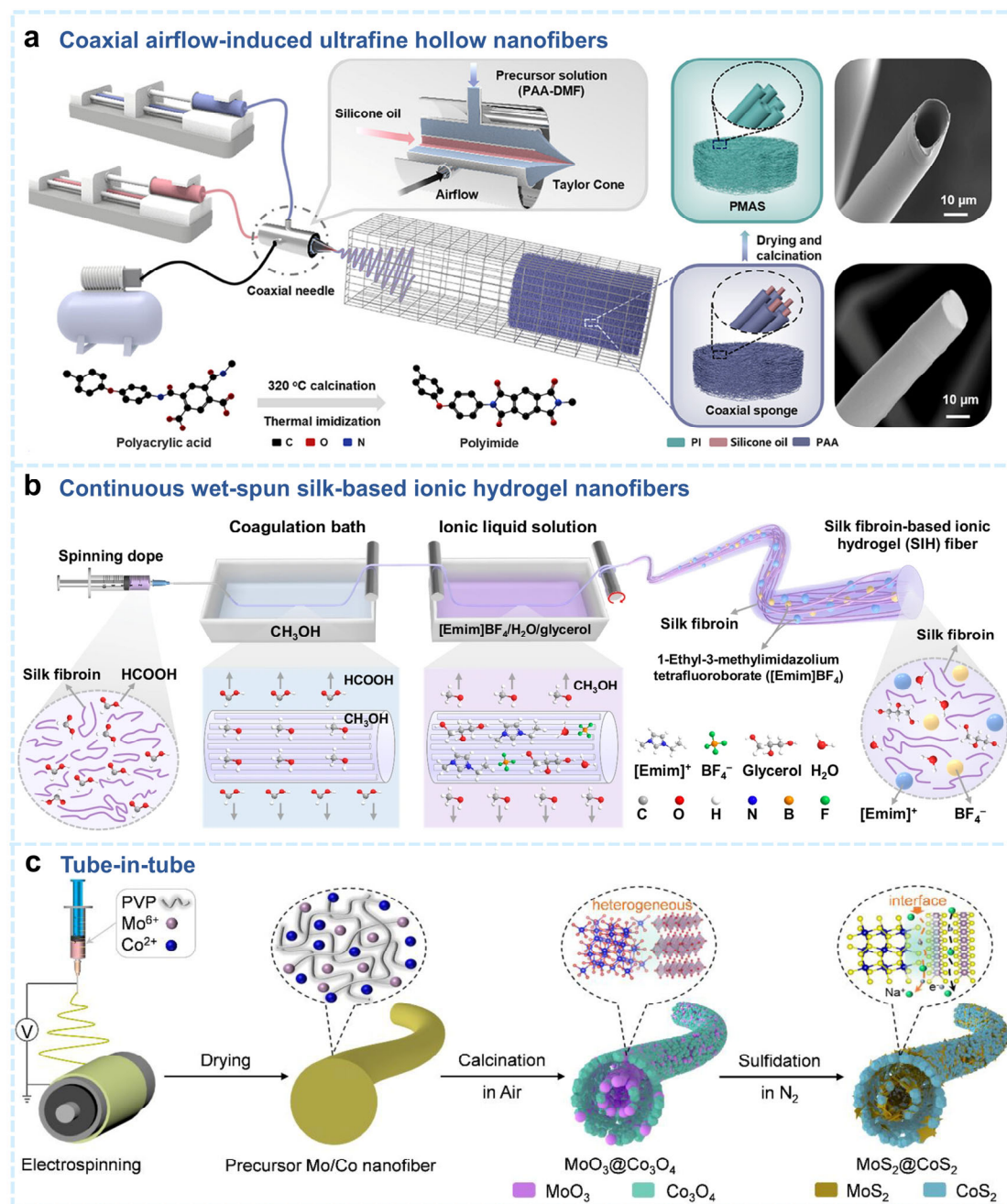


Figure 5. Schematic illustration of fiber fabrication strategies for functional NFs. (a) Coaxial airflow-induced ultrafine hollow NFs. Reproduced with permission [120]. Copyright 2025, Wiley-VCH GmbH. (b) Continuous wet-spun silk-based ionic hydrogel NFs. Reproduced with permission [121]. Copyright 2024, Springer Nature. (c) Fabrication of tube-in-tube structured MoS₂@CoS₂ NFs via electrospinning followed by calcination and sulfidation. Reproduced with permission [122]. Copyright 2024, Elsevier.

2.5.2. Wet-Coagulation Spinning

Wet-coagulation spinning represents an important method for fabricating bio-based flexible fibers, relying fundamentally on solvent exchange between the coagulation-bath solvent and the spinning dope to induce phase separation and solidification of the polymer; this process can further be coupled with subsequent liquid-phase modification treatments to achieve functionalized fiber modification [123,124]. For example, Lu et al. employed a continuous wet-coagulation spinning process to fabricate silk-based ionic hydrogel NFs, natural silk fibroin was first dissolved in formic acid to disrupt intramolecular hydrogen bonding within the protein, thereby preparing a stable, spinnable dope (Figure 5b) [121]. The spinning solution, upon extrusion through the spinneret, entered a methanol coagulation bath, where rapid solvent exchange induced protein-molecule aggregation and precipitation, fixing the morphology of the continuous nascent fiber. To enhance fiber performance, the nascent fibers were further immersed in a composite modification solution containing [Emim]BF₄ ionic liquid, glycerol, and water,

whereby the ionic liquid became stably anchored within the protein network and glycerol exerted a plasticizing effect, effectively eliminating fiber brittleness and ultimately yielding an ionic hydrogel fiber of excellent flexibility. This fiber possesses continuous, interconnected ion-transport channels and exhibits stable ionic conductivity, rendering it suitable for wearable sweat sensing, flexible ionic skin, and other flexible electronic devices. This work demonstrates that fiber systems can achieve sensing-capable polymer fibers through precise interfacial chemical design, without compromising biocompatibility.

2.5.3. Electrospinning Coupled with High-Temperature Modification

Electrospinning coupled with high-temperature modification constitutes an efficient fabrication strategy for constructing inorganic composite fibers, implemented via a two-step process: first, uniaxial electrospinning is employed to fabricate precursor fibers uniformly loaded with functional components; subsequently, staged, atmosphere-controlled high-temperature thermal treatment is applied to achieve phase transformation and fine structural regulation of the material [125,126]. For example, Gao et al. employed this composite process to fabricate tube-in-tube $\text{MoS}_2@\text{CoS}_2$ heterostructured NFs, using PVP as the fiber-forming carrier to uniformly complex Mo and Co bimetallic ions, thereby preparing a stable, homogeneous spinning precursor solution; following uniaxial electrospinning and drying treatment, an organic composite precursor fiber with uniformly dispersed metal components was obtained (Figure 5c) [122]. Structural modification was accomplished through a two-stage controlled high-temperature thermal treatment: calcination was first carried out under an air atmosphere to completely decompose the organic carrier while simultaneously promoting in situ oxidation of the metal ions, generating morphologically intact $\text{MoO}_3@\text{Co}_3\text{O}_4$ core-shell oxide fibers; subsequently, sulfidation treatment was performed under an inert nitrogen atmosphere, converting the metal oxides in situ into the bimetallic sulfides MoS_2 and CoS_2 , and, relying on a template self-exfoliation effect, forming a distinctive bilayer tube-in-tube hierarchical structure that establishes an abundance of heterogeneous reactive interfaces. This process is capable of precisely reconciling fiber morphological retention with phase-structure regulation, and the resulting porous heterostructured fibers possess abundant active sites, conferring notable application advantages in electrochemical energy storage and electrocatalytic electrode materials.

3. Synthesis of Functional Materials via Electrospinning

The performance of NF-based wearable electronic devices is fundamentally dependent upon the underlying functional fiber material system. Different functional materials exhibit inherent differences in conductive transport mechanisms, mechanical compliance, environmental stability, and biocompatibility, which directly determine the sensing sensitivity, long-term service reliability, and biointerface compatibility of wearable devices. Elucidating the mechanisms by which the intrinsic properties of materials govern the core performance of devices therefore constitutes a central scientific question in establishing a materials-science theoretical framework for high-performance NF-based wearable electronics. On this basis, the present section examines functional NF material systems constructed via electrospinning, focusing on polymeric NFs, metal oxide and their composite NFs, MXene-based composite NFs, carbon NFs, and other functionally structured NFs. The fabrication strategies, microstructural regulation, and relationships to wearable electronic applications of each material class are analyzed, thereby providing theoretical grounding and technical direction for the structural design, fabrication, and device development of high-performance electrospun NFs for wearable applications.

3.1. Polymer NFs

Polymeric NFs constitute one-dimensional flexible polymer substrates fabricated at scale via electrospinning, with controllable microstructures, including solid, porous, core-shell, and hollow architectures, attainable through processing-parameter regulation. Polymer substrates suited to human-skin sensing must satisfy requirements of low modulus, high stretchability, resistance to sweat-induced corrosion, and good spinnability, rendering them broadly applicable in flexible wearable sensing [54,127]. For example, Cho et al. systematically investigated the quantitative relationship between spinning process parameters and the microscale morphology of polymer fibers, employing SEM and TEM characterization to resolve fiber cross-sectional configurations under varying processing conditions and establishing a correspondence between key parameters, solution concentration, solvent ratio, and collector-drum speed, and four categories of fiber architecture: solid, porous, core-shell, and hollow (Figure 6a) [68]. When fiber diameter was reduced below a critical size of 200 nm, the electric-field polarization effect was markedly enhanced, such that the fraction of the piezoelectrically active β -phase within the fiber exceeded 70%, substantially higher than the ~50% ceiling typical of conventional thin-film processes, thereby achieving a concomitant improvement in piezoelectric output and sensing sensitivity. This work establishes a

mapping between processing conditions and resulting morphology, offering valuable guidance for the crystalline-phase optimization of PVDF piezoelectric fibers.

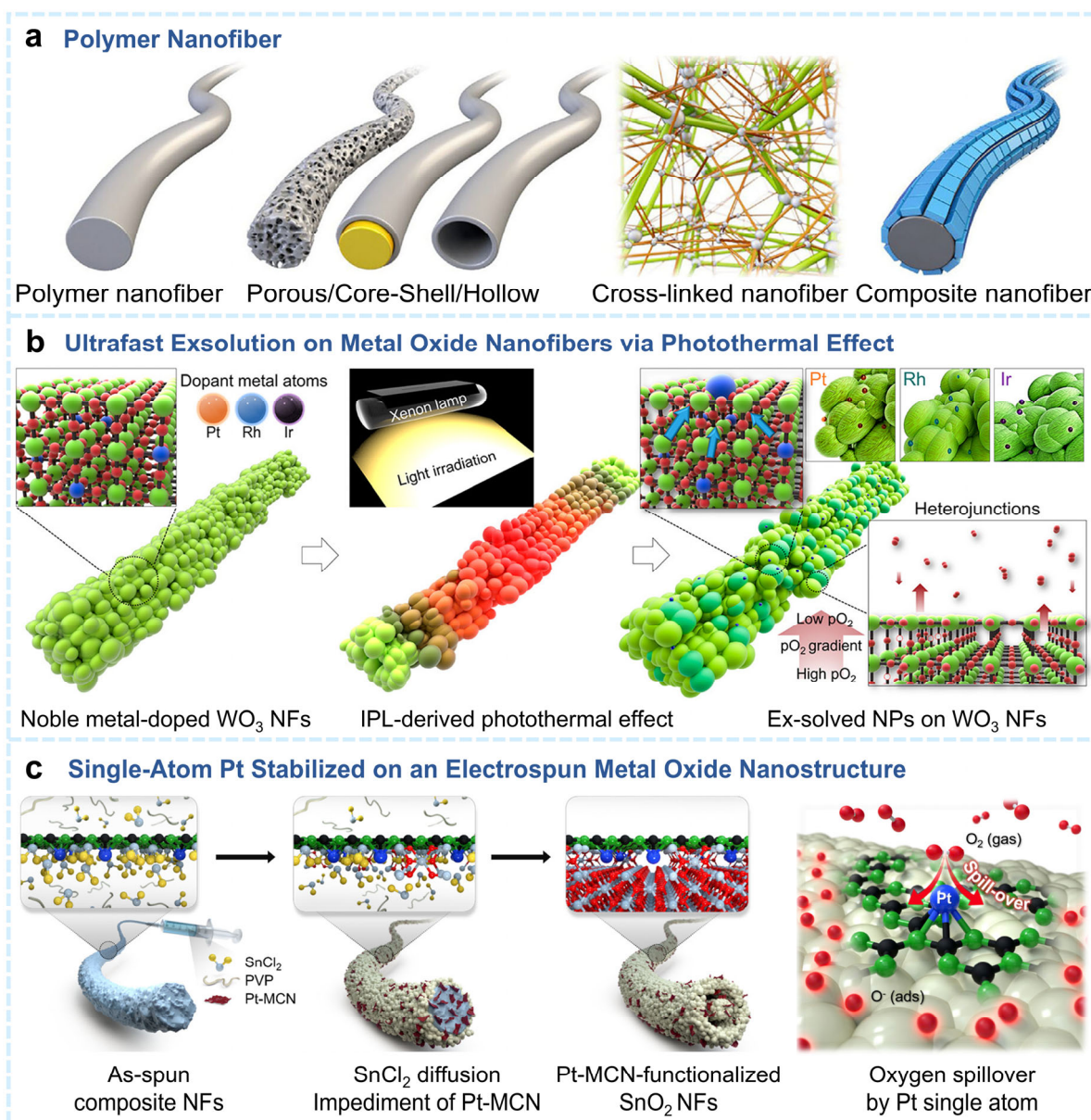


Figure 6. Diverse structural configurations of electrospun polymer and metal oxide NFs. (a) Polymer NF. Reproduced with permission [68]. Copyright 2025, Wiley-VCH GmbH. (b) Ultrafast exsolution on metal oxide NFs via photothermal effect. Reproduced with permission [128]. Copyright 2022, American Chemical Society. (c) Single-atom Pt stabilized on an electrospun metal oxide nanostructure. Reproduced with permission [129]. Copyright 2020, American Chemical Society.

Distinct polymer matrices exhibit substantial intrinsic differences and must therefore be selected in accordance with the specific requirements of the wearable sensing application. Thermoplastic polyurethane (TPU), characterized by a high elongation at break, low residual strain, and excellent elasticity together with versatile solvent processability, constitutes the predominant flexible substrate for high-strain, high-sensitivity pressure sensors [99]. PAN, owing to its high carbon content and superior thermal stability, is commonly employed as a precursor for fabricating conductive carbon NFs [130]. PVDF and its copolymer P(VDF-TrFE) possess intrinsic piezoelectric activity, rendering them core materials for self-powered vibration and impact sensors [131]. Natural protein fibers such as silk fibroin and collagen exhibit excellent biocompatibility and biodegradability, conferring distinctive application advantages in disposable electronic skin and implantable sensing devices [132]. In addition, polymers such as poly(lactic acid) (PLA), polyimide (PI), and PVA have likewise received extensive research attention, offering biodegradability, high-temperature resistance, and high hydrophilicity, respectively, to meet various niche flexible-sensing requirements [133].

3.2. Metal Oxides and Composite NFs

Metal oxide and composite NFs constitute porous inorganic functional materials combining favorable electrical and electrochemical properties, and are predominantly fabricated via a two-step process coupling electrospinning with high-temperature calcination, enabling precise construction of a continuous one-dimensional skeleton with a porous microstructure [134,135]. The fabrication procedure entails blending metal salts (e.g., acetates or chlorides) with spinnable polymers such as PVP or PAN to formulate the spinning solution, electrospinning to obtain composite precursor fibers, and subsequently calcining at 300–1200 °C to remove the organic component, thereby promoting decomposition and crystallization of the metal salt to yield high-purity, single-crystalline porous fibers. Thermal decomposition of the organic component generates interconnected pore channels within the fiber, conferring a high specific surface area on the order of tens to hundreds of m²/g, far exceeding that achievable with sputtered or vapor-deposited thin films. Such fibers have accordingly been widely employed in flexible sensing, gas detection, and electrochemical devices.

Exploiting the structural advantage of the high specific surface area characteristic of this class of fibers, the ultrafast photothermal exsolution method enables rapid construction of noble-metal/metal-oxide heterojunctions, representing a highly efficient interfacial modification strategy [136]. For example, Shin et al. employed this process to generate ultrafine noble-metal heterostructured particles in situ on the surface of noble-metal-codoped WO₃ NFs (Figure 6b) [128]. Millisecond-scale pulsed illumination induces an instantaneous, transient high-temperature spike that drives the exsolution of metal ions from the crystal lattice, while the brief thermal duration effectively suppresses particle coarsening, yielding noble-metal particles with a uniform size of only 1–2 nm and thereby substantially increasing the density of active sites at the heterojunction. This system achieves room-temperature ultratrace detection of NO_x and NH₃, with a detection limit below 1 ppb, offering marked advantages over conventional modification approaches such as impregnation and atomic layer deposition. Beyond the ultrafast photothermal exsolution method, researchers have further enhanced gas-sensing performance through interfacial modification strategies such as noble-metal decoration and heterostructure construction. For instance, Shin et al. proposed a single-atom modification strategy in which Pt single atoms were anchored at oxygen-vacancy sites of electrospun SnO₂ fibers via Pt–O–Sn chemical bonds (Figure 6c) [129]. A staged, temperature-controlled calcination process achieved atomically uniform dispersion of Pt, and the resulting dual catalytic synergy markedly enhanced hydrogen-sensing performance: Pt substantially lowered the activation energy for hydrogen dissociation while simultaneously broadening the gas-sensing reactive interface through an oxygen-spillover effect, ultimately yielding a 12-fold enhancement in hydrogen-detection sensitivity and a detection limit as low as 5 ppm. This work elucidates the sensitization mechanism underlying single-atom catalysis and offers a conceptual approach for atomic-scale regulation of sensing interfaces.

3.3. MXene-Based Composites NFs

MXene-based composite NFs are one-dimensional flexible conductive fibers fabricated via processing techniques such as wet spinning and electrospinning, in which two-dimensional MXene nanosheets serve as the core functional phase, supplemented by auxiliary components such as polymers, carbon nanotubes, or cellulose [137]. MXene itself combines high electrical conductivity, abundant surface-active sites, and a tunable interlayer architecture, rendering it an ideal conductive filler for flexible sensing and electrochemical energy storage; however, pure MXene fibers are highly prone, during fiber formation, to shortcomings such as nanosheet restacking, poor interfacial bonding, and difficulty in simultaneously enhancing mechanical and electrical properties. Consequently, the incorporation of a second phase to construct composite systems has become a mainstream research direction in this field [138]. To address these inherent limitations, current research primarily focuses on regulating nanosheet orientation, constructing carbon-based conductive bridges, and building multilevel ordered architectures, thereby simultaneously optimizing the overall performance of the fiber.

Studies centered on axial-orientation regulation and carbon-nanotube interlayer bridging have been employed to enhance the overall fiber performance. For example, Zhou et al. proposed a static–dynamic densification continuous fabrication strategy combining static incorporation of short CNTs with dynamic hot-drawing of PLA, enabling the scalable production of kilometer-scale, ultralong composite fibers. Short CNTs embedded between MXene layers function as conductive bridges, while hot-drawing induces the MXene nanosheets to align in a highly regular manner along the fiber axis; concurrently, thermal decomposition of PLA promotes interlayer hydrogen bonding, substantially reducing the internal porosity of the fiber (down to 4.2%) and increasing the nanosheet orientation factor to 0.945 (Figure 7a) [139]. This highly ordered axial architecture optimizes the stress-transfer pathway and suppresses interlayer sliding of the MXene nanosheets, yielding fibers with a tensile strength of 941.5 MPa and an internal MXene core-layer electrical conductivity as high as 12,836.4 S cm^{−1}. Smart textiles

woven from these fibers enable battery-free human health monitoring and human-machine interactive remote control, establishing a generalizable fabrication paradigm for high-strength conductive textile electronics.

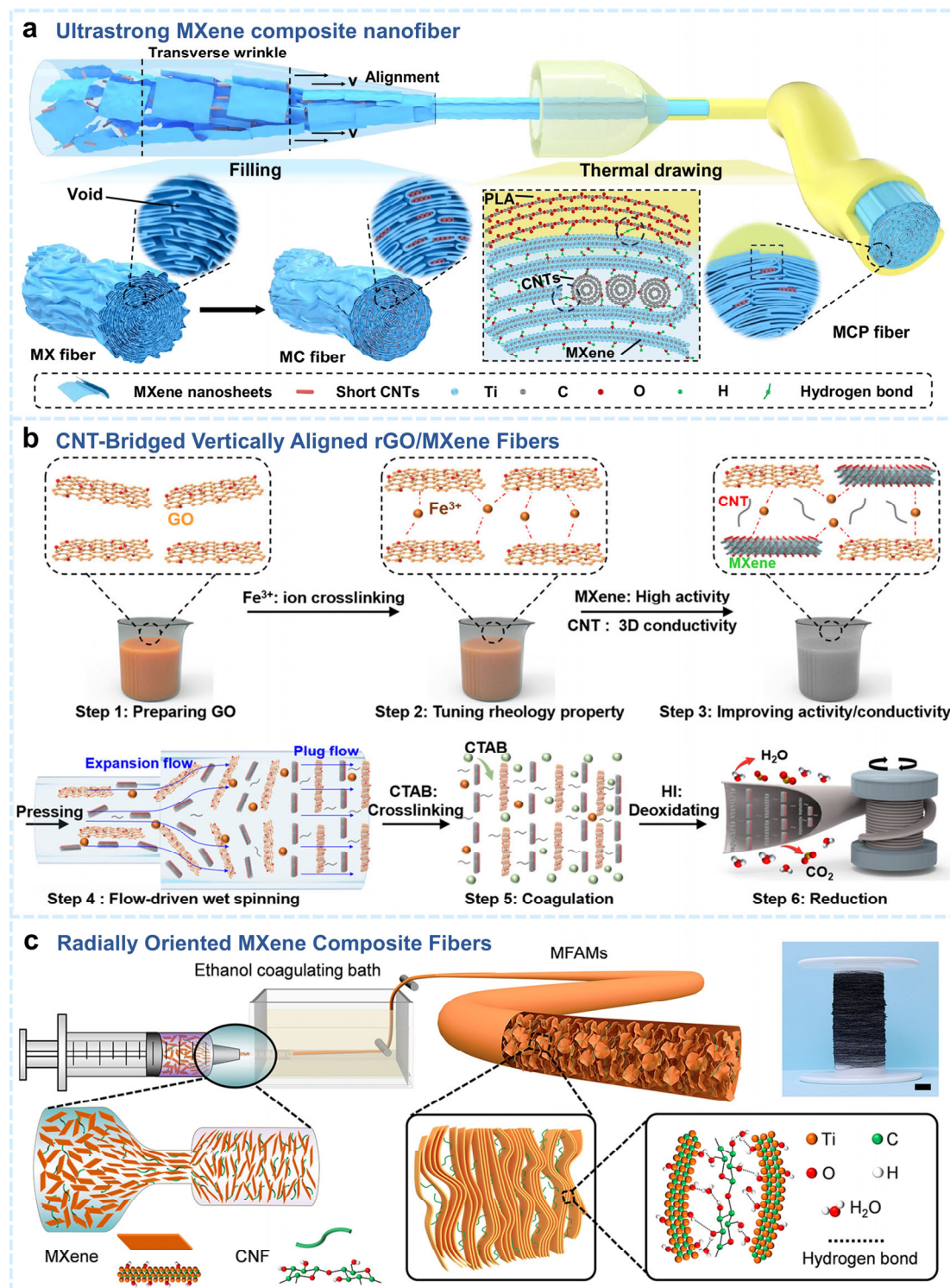


Figure 7. Schematic Illustration for Fabrication of MXene-Based NFs. (a) Ultrastrong MXene composite NF. Reproduced with permission [139]. Copyright 2025, Springer Nature. (b) CNT-bridged vertically aligned rGO/MXene fibers. Reproduced with permission [140]. Copyright 2025, Wiley-VCH GmbH. (c) Radially oriented MXene composite fibers. Reproduced with permission [141]. Copyright 2025, American Association for the Advancement of Science.

Beyond axial one-dimensional alignment schemes, precise flow-field regulation can be used to construct a vertically arranged nanosheet architecture, substantially shortening ion-transport distances. For instance, Guan et al. developed a flow-field-driven wet-spinning process coupled with ionic crosslinking to fabricate CNT-bridged,

vertically aligned rGO/MXene composite fibers (Figure 7b) [140]. This system employs Fe^{3+} to regulate the rheological properties of the GO dispersion, and the resulting CNT–vertically aligned–GMF (CNT-VA-GMF) electrode exhibits excellent ion-transport properties, an outstanding specific capacitance (740 F g^{-1}), and remarkable long-term cycling stability (98% capacity retention after 30,000 cycles) in H_2SO_4 electrolyte. The vertically arranged open channels substantially shorten the electron-transport pathway and accelerate ion-diffusion kinetics, endowing this fiber electrode with excellent electrical conductivity and electrochemical energy-storage capability, rendering it well suited to high-performance fiber-shaped supercapacitors.

Distinct from axial and vertical alignment configurations, radial arrangement constitutes a distinctive architecture suited to stimulus-responsive actuator devices. For example, Fu et al. employed wet spinning combined with ethanol-coagulation-bath-induced assembly, exploiting the flow-field gradient during spinning to eliminate axial shear forces and thereby achieve synergistic, radially ordered arrangement of MXene nanosheets and cellulose NFs (CNFs), with hydrogen bonding between the two components reinforcing interfacial adhesion (Figure 7c) [141]. This radial configuration possesses high modulus along both the axial and radial dimensions, simultaneously enhancing load-transfer efficiency and establishing a continuous electron-transport pathway. Leveraging a temperature-induced, reversible hydrogen-bond reconstruction effect, the fiber achieves 21.0% reversible thermally induced contraction, delivering high-stroke artificial-muscle-like actuation without requiring twisting, conferring distinctive application value in smart textiles and soft robotics. Taken together, precise regulation of the spatial orientation of MXene nanosheets and their interfacial interactions overcomes the performance limitations arising from the disordered stacking characteristic of pure MXene fibers. The combination of axial, vertical, and radial multilevel ordered architectures with CNT-bridging reinforcement strategies enables the simultaneous optimization of electron conduction, ion diffusion, and stress-transfer behavior, reconciling mechanical strength, electrical conductivity, and electrochemical/stimulus-responsive functionality within a single fiber—thereby providing strong support for the application of MXene composite fibers in smart textiles, robotic arms, and robotic grippers.

3.4. Carbon-Based NFs (CNFs)

Carbon-based NFs are one-dimensional carbonaceous conductive materials formed via processes such as electrospinning followed by carbonization or wet spinning; they transcend the singular mechanical-support role characteristic of purely polymeric fibers, combining high electrical conductivity with electrochemical activity while possessing a continuous porous network and a high specific surface area, and have thus become core functional substrates for flexible wearable sensing, fiber-based energy storage, and soft actuator devices [142,143].

Addressing the critical bottleneck whereby macroscopic CNT fiber bundles rely solely on weak van der Waals interactions between adjacent bundles, resulting in inefficient load transfer and measured mechanical properties far below the theoretical limit. Li et al. proposed a covalent-bridging reinforcement strategy employing rigid π -conjugated polymers (Figure 8a) [144]. PIPD-type conjugated polymers were dry-spun together with CNTs, and a boronic-acid crosslinking agent was introduced to construct a stable B–O–C covalent-bond network between adjacent CNT bundles, elevating the interbundle binding energy from 0.5 eV/nm to 3 eV/nm. This covalent interface substantially optimizes stress transfer and suppresses interbundle sliding, yielding fibers with a tensile strength exceeding 4 GPa while maintaining an electrical conductivity above 10^4 S/m , achieving simultaneously high strength and high conductivity, and thereby providing a high-performance carbon-based fiber construction strategy for high-strain sensors and artificial muscles.

Beyond intrinsic modification of pure CNT fibers, hybridization with two-dimensional carbon fillers offers another route to enhancing NF conductivity. For example, Ryu et al. constructed oxygen-free graphene/ Co_3O_4 composite electrospun fibers, revealing a synergistic cross-particle conduction mechanism enabled by two-dimensional carbon nanosheets (Figure 8b) [145]. Employing PBA-induced π – π interactions, graphene was uniformly anchored onto the surface of the Co_3O_4 fibers, establishing continuous conductive pathways between oxide grains and converting interparticle potential-barrier-hopping conduction into low-resistance ballistic conduction; the resulting composite fiber exhibited a room-temperature electrical conductivity more than three orders of magnitude higher than that of pure Co_3O_4 . This modification strategy obviates the need for high-temperature reduction or calcination, and its mild fabrication conditions render it broadly applicable to diverse oxide-based gas-sensing and electrochemical fibers, conferring considerable generality.

The fabrication of carbon-based fibers is highly dependent on raw-material sourcing, entailing high production costs and poor sustainability; biomass-derived carbon sources offer a targeted solution to this limitation. For example, Liu et al. developed a three-step green fabrication process for lignin-derived, aligned single-walled carbon nanotube (SWCNT) macroscopic fibers (Figure 8c) [146]. Renewable lignin was employed

as the carbon precursor and pyrolyzed at temperatures above 900 °C to generate a reducing gas mixture, from which high-quality SWCNTs were grown via a vapor–liquid–solid mechanism catalyzed by Fe/S catalysts; the resulting CNTs were dissolved in chlorosulfonic acid to form a liquid-crystalline spinning dope, which was wet-spun into highly aligned continuous fibers. This biomass-derived fiber achieves an electrical conductivity of up to 10^5 S/m and a tensile strength of 3.2 GPa (performance metrics on par with commercial high-purity CNT fibers), while reducing raw-material costs by approximately 40-fold, thereby offering a novel pathway toward the scalable, green manufacturing of high-performance conductive fibers.

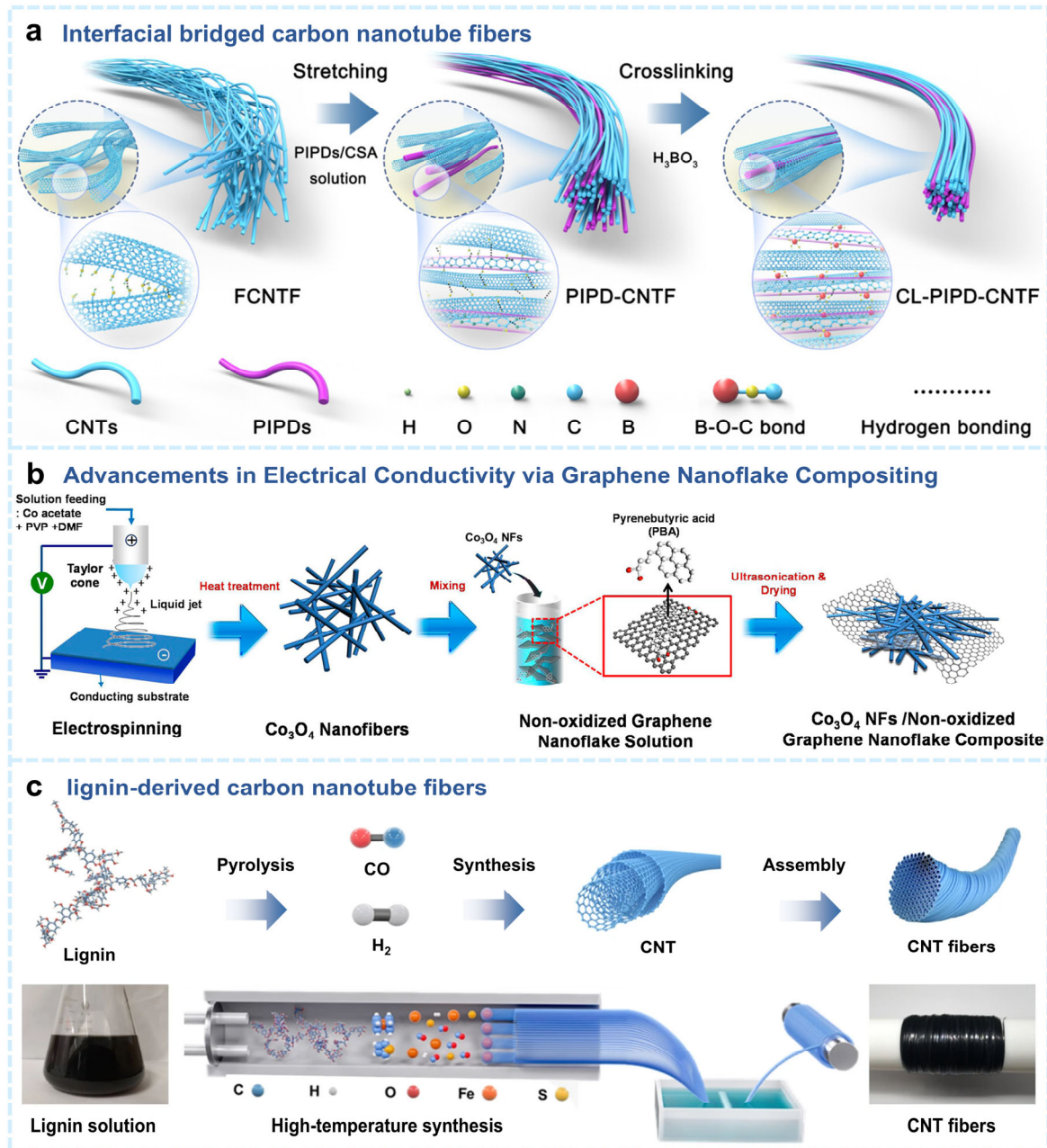


Figure 8. Carbon-based NF fabrication. (a) Interfacial bridged carbon nanotube fibers. Reproduced with permission [144]. Copyright 2025, American Chemical Society. (b) Advancements in electrical conductivity via graphene nanoflake compositing. Reproduced with permission [145]. Copyright 2013, American Chemical Society. (c) lignin-derived carbon nanotube fibers. Reproduced with permission [146]. Copyright 2022, Springer Nature.

In summary, carbon-based NFs can address three core challenges, mechanical mismatch among nanotube bundles, insufficient conductivity of metal oxides, and prohibitively high fabrication costs, through three respective strategies, covalent interfacial reinforcement, two-dimensional carbon hybridization, and substitution with biomass-derived feedstocks. Following structural and interfacial optimization, carbon-based fibers integrate high electrical conductivity, a high specific surface area, and excellent stretchability, conferring broad application potential in wearable human-body sensing, fiber-based energy storage, and soft robotics.

3.5. Other Structured NFs

NF aerogels integrate the microstructural characteristics of electrospun NFs with the three-dimensional porous network advantages of aerogels, representing an advanced form of high-performance fiber-based porous material [147,148]. The structural parameters, fabrication processes, and core performance metrics of NF aerogels across different material systems are summarized in Table 2, comparing the overall performance advantages and technical differentiation of this class of materials. Relative to conventional rigid porous materials such as silica- or carbon-based aerogels, NF aerogels employ flexible fibers as the structural skeleton, combining excellent structural compressibility with mechanically resilient recovery, thereby effectively overcoming the inherent brittleness, susceptibility to collapse, and poor fatigue resistance characteristic of conventional aerogels [149]. Relative to densified electrospun nanofibrous membranes, the distinctive three-dimensional open porous network of NFs aerogels affords higher porosity, greater specific surface area, and lower intrinsic thermal conductivity, conferring notable synergistic structural and performance advantages in cutting-edge applications such as advanced thermal management, flexible intelligent sensing, and electrochemical energy storage [150].

Table 2. Advantages and disadvantages of various fiber-based composite materials.

Materials	Methods	Advantages	Disadvantages
Nanofiber/Hydrogel	Spin coating	Uniform ultrathin film; excellent thickness controllability	Limited scalability; low material utilization
	Drop coating	Cost-effective; suitable for large-area deposition	Poor thickness uniformity; limited reproducibility
	In situ gelation	Strong interfacial integration; enhanced structural stability	Long gelation time; sensitive to environmental conditions
	Coaxial electrospinning	One-step fabrication of core-shell architectures	Complex process control; nozzle clogging risk
Nanofiber/aerogel	Freeze-drying	Highly porous 3D network; ultralow density	Energy-intensive process; poor mechanical robustness
	Electrospinning-assisted assembly	Tunable microstructure; interconnected conductive pathways	Multi-step fabrication; limited production efficiency

To address the limitation of conventional aerogel fibers exhibiting a singular mechanical profile, wherein strength/toughness and resilience are difficult to reconcile simultaneously, Hu et al. proposed a bioinspired hierarchical strategy to fabricate honeycomb-structured aramid NFs (ANF) aerogel fibers (Figure 9a) [151]. Kevlar fiber was employed as the raw material and dissociated via DMSO/KOH treatment to obtain monodisperse ANF colloidal suspensions with lengths exceeding 10 μm ; a covalent interfiber crosslinking network was then constructed using 1,4-dibromobutane, and, combined with freeze-templated assembly and supercritical CO_2 drying, an aligned, honeycomb-structured three-dimensional porous architecture was successfully achieved. This architecture realizes efficient synergy between mechanical strength and elasticity: the compressive strength along the aligned direction reaches 180 kPa (at 50% strain), while, along the perpendicular direction, the resilience remains above 95% even after 1000 cycles of 50%-strain compression, placing its mechanical performance among the best reported for comparable materials. The fiber simultaneously exhibits an ultralow thermal conductivity of 18 $\text{mW}/(\text{m}\cdot\text{K})$, conferring considerable application value in wearable high-temperature protection and aerospace thermal management.

Wet spinning enables the continuous extrusion and gelation of precursor solutions, providing an effective route to the controlled fabrication and continuous production of one-dimensional porous structures [152]. However, during solvent exchange and drying, the gel network is prone to shrinkage or collapse under capillary stress, which compromises the pore architecture. In addition, solvent consumption, drying energy demand, and process stability continue to hinder large-scale implementation [153]. To address the high cost and limited continuity of conventional aerogel fiber fabrication, Xue et al. integrated in situ UV crosslinking into the wet-spinning process to construct a robust crosslinked polyimide gel skeleton. Combined with ambient-pressure drying, this approach effectively preserved the porous structure (Figure 9b) [154]. By avoiding supercritical drying, the strategy improves pore retention while reducing fabrication cost, highlighting the potential of in situ network construction during spinning to synergistically regulate fiber formation and drying stability. Overall, wet spinning combines continuous shaping with versatile structural design. Nevertheless, achieving high porosity retention, low solvent consumption, and stable scale-up will require further optimization of gel-network construction and post-treatment processes.

To meet the demand of flexible pressure sensing for materials exhibiting a broad linear response range and high mechanical sensitivity, Fu et al. employed a microfluidic spinning platform to precisely construct axially

density-graded aramid aerogel fibers (Figure 9c) [155]. By regulating the microfluidic system, a continuous, linear axial gradient in ANF concentration (0.5–3 wt%) and density (2–20 mg/cm³) was achieved within a single fiber. This distinctive gradient architecture confers upon the GAF a superior hierarchical mechanical response: during compression, the low-density regions undergo preferential elastic buckling while the high-density regions provide rigid support, synergistically yielding a near-ideal linear stress–strain response ($R^2 > 0.99$) that effectively resolves the nonlinear stress-locking issue characteristic of homogeneous aerogels, providing an excellent structural design solution for wide-range, highly stable flexible pressure-sensing materials.

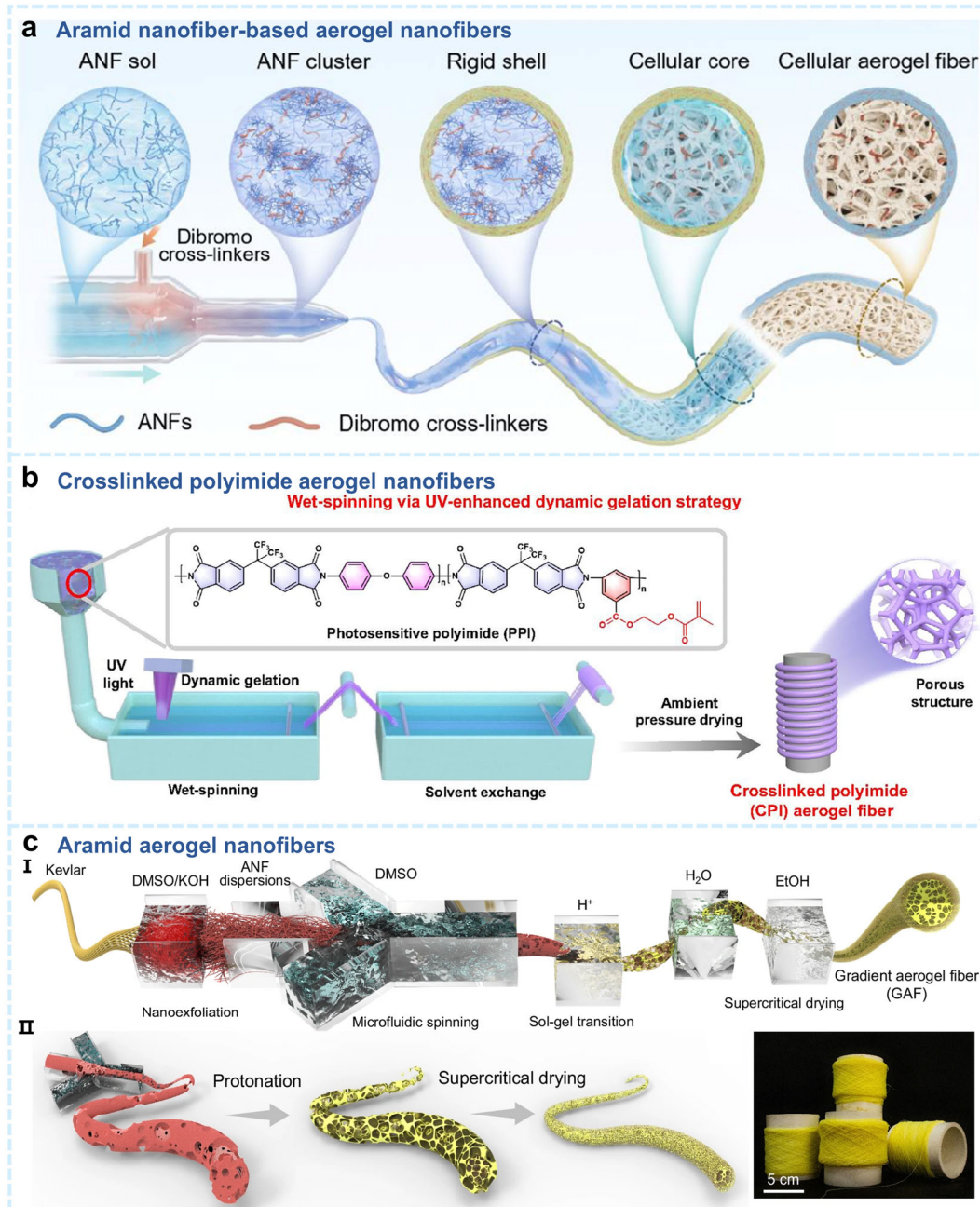


Figure 9. Schematic illustration of the fabrication process of aerogel NFs. **(a)** Aramid NF-based aerogels NFs. Reproduced with permission [151]. Copyright 2026, Springer Nature. **(b)** Crosslinked polyimide aerogel NFs. Reproduced with permission [154]. Copyright 2023, Springer Nature. **(c)** Aramid aerogel NFs. Reproduced with permission [155]. Copyright 2025, Springer Nature.

4. Applications

4.1. Physiological Sensing

To enable long-term, high-fidelity monitoring of human physiological signals, flexible electronic devices are progressively evolving from conventional two-dimensional patches toward one-dimensional fiber bioelectronic

devices. Compared with planar devices, fibers combine excellent compliance, breathability, and textile compatibility, enabling more stable and conformal integration with the human body and allowing direct incorporation into smart textiles for continuous, long-term physiological signal acquisition. Research priorities in this field have correspondingly shifted from reliance on intrinsic conductive material performance improvement toward biomimetic structural design, multi-scale conductive network construction, and functional device integration, with the aim of simultaneously advancing mechanical adaptability, signal stability, and system integration capability.

To address the susceptibility of fiber devices to stress concentration and conductive network instability during complex human motion, Zhou et al. drew inspiration from the helical winding architecture of climbing plant stems and designed a mechanically adaptive electronic biofiber with a negative Poisson's ratio (Figure 10a) [156]. This fiber achieves deformation redistribution through its helical topological structure, effectively mitigating local stress concentration and maintaining conductive pathway continuity during stretching, thereby enabling precise decoding of lower-limb micro-strain patterns and functioning as an embodied intelligent sensing unit for long-term biomechanical monitoring. This work introduces biomimetic mechanical architecture into fiber bioelectronic devices, providing new structural design concepts for simultaneously achieving mechanical adaptability and sensing stability.

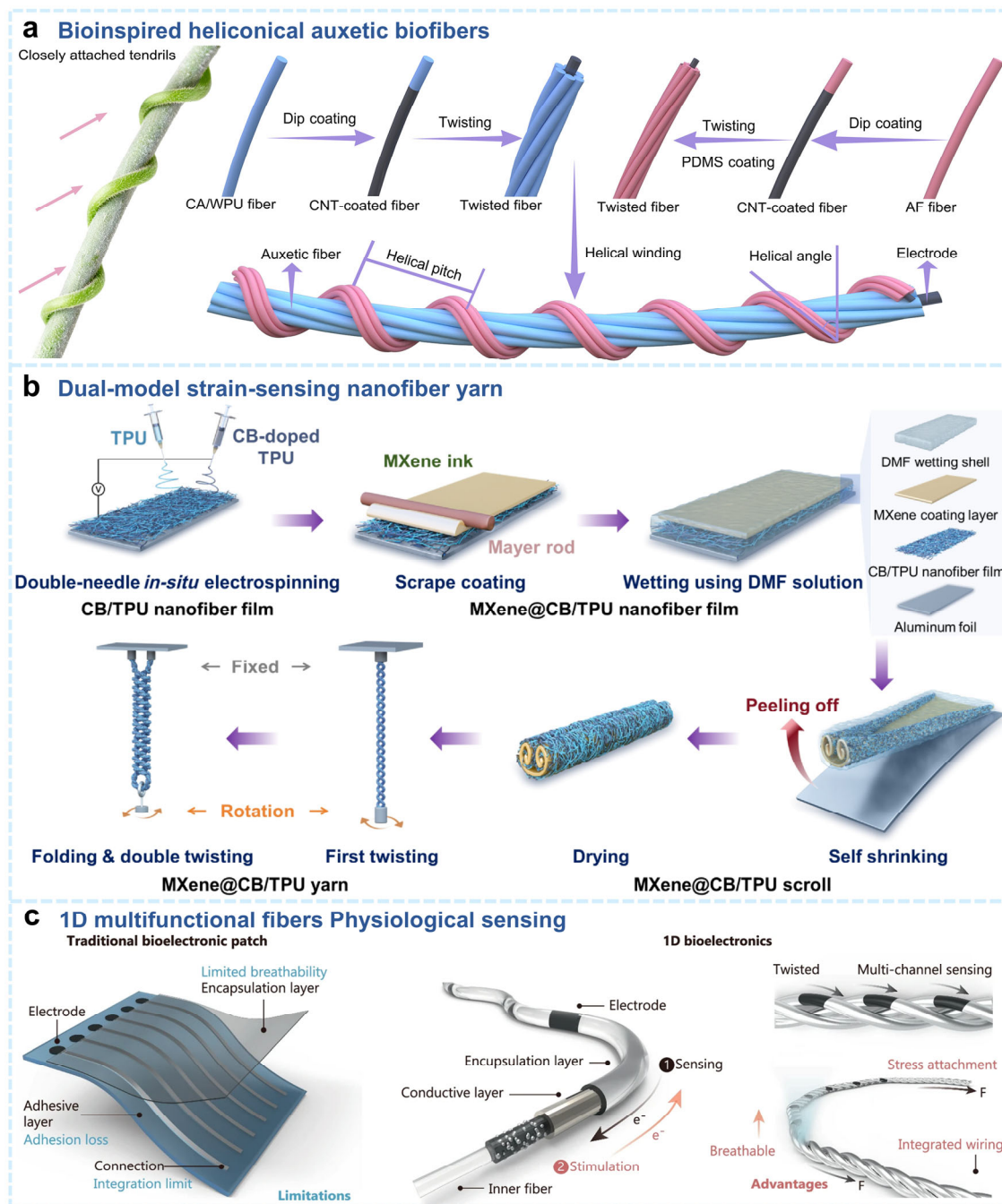


Figure 10. Applications of wearable NF electronic devices in physiological sensing. (a) Mechanically adaptive electronic fiber with a negative Poisson's ratio for biomechanical sensing. Reproduced with permission [156].

Copyright 2026, The American Association for the Advancement of Science. (b) Self-contracting, self-twisting MXene@CB/TPU composite NF yarn. Reproduced with permission [157]. Copyright 2026, Tsinghua University Press. (c) Scalable, stretchable one-dimensional multifunctional fiber for multimodal sensing. Reproduced with permission [16]. Copyright 2026, Springer Nature.

Building on this foundation, and with the aim of further reconciling multimodal sensing capability with device stability, Tang et al. constructed a self-contracting, self-twisting MXene@CB/TPU composite NF yarn (Figure 10b) [157]. This work employs an MXene conductive layer, CB-doped conductive NFs, and an elastic TPU matrix to construct a hierarchical conductive network, combined with a self-coiling and dual-twist structure to achieve synergistic regulation of strain and pressure responses. Smart textiles constructed from a single sensing yarn can simultaneously monitor dynamic physiological signals, including joint bending, heart rate, and respiration, while also resolving static pressure variations induced by finger pressing, plantar pressure, and different sitting postures, validating the developmental trajectory of fiber devices from single mechanical sensing toward multi-scenario, multimodal health monitoring.

As fiber bioelectronics advances toward higher integration and multifunctionality, sensing capability alone is no longer sufficient to meet the demands of next-generation intelligent medical systems; research priorities have accordingly expanded to encompass the monolithic integration of sensing, stimulation, and energy transmission. Yin et al. proposed a one-dimensional liquid-metal multifunctional fiber fabricated via a solution deposition strategy, seamlessly integrating conductive pathways and functional electrodes within a single fiber structure (Figure 10c) [16], simultaneously realizing electrophysiological signal acquisition, *in vivo* neural stimulation, and wireless energy transmission. By virtue of its outstanding electrical conductivity, stretchability, biocompatibility, and electrochemical stability, this work transcends the single-function limitation of conventional fiber devices and provides a new design paradigm for constructing next-generation fiber bioelectronic platforms that synergistically integrate sensing, therapy, and energy management.

4.2. Biological Signal Detection

Biosignal detection represents one of the core application directions of NF-based wearable sensing with the greatest clinical translational value [158]. The inherently weak amplitude of physiological signals, coupled with the complex noise environments typically encountered during detection, readily gives rise to signal distortion and acquisition failure, constituting a persistent core technical bottleneck in this field [159]. NF-based sensing platforms combine ultrahigh sensing sensitivity with excellent conformability to curved surfaces, effectively suppressing motion artifacts and interfacial interference, and thereby offer an ideal material system for high-precision, highly stable physiological signal detection.

Implantable neural signal recording imposes stringent requirements on the mechanical compliance and long-term interfacial stability of electrodes. Conventional metallic electrodes suffer from excessive stiffness, a propensity to elicit inflammatory responses upon chronic implantation, and a characteristic postoperative impedance surge that severely compromises signal quality; achieving synergistic optimization of flexibility and high electrical conductivity constitutes the central scientific challenge in this direction. Zhang et al. exploited the liquid-crystalline shear-induced self-assembly behavior of graphene oxide to fabricate highly aligned (Figure 11a) [160], pure graphene fiber microelectrodes with a diameter of 25 μm via wet spinning, whose mechanical stiffness closely matches that of brain tissue. These electrodes-maintained impedance consistently below 100 k Ω throughout four weeks of *in vivo* implantation and achieved a stable signal-to-noise ratio exceeding 5 for visually evoked potentials, validating the long-term viability of flexible carbon-based fiber electrodes for chronic brain-machine interface applications.

Self-powered design represents a critical pathway toward resolving the chronic energy-supply bottleneck of wearable physiological sensing systems. Conventional active sensors rely on external power sources, inherently confronting the trade-off between limited battery lifetime and large system volume in continuous monitoring scenarios; a self-driven strategy that directly transduces mechanical energy into sensing signals can fundamentally eliminate dependence on external power supply. Lin et al. employed a highly elastic TPU NF scaffold and constructed a periodic sinusoidal buckled microstructure via a pre-stretching process; dynamic structural deformation triggers a triboelectric effect (Figure 11b) [161], generating an open-circuit voltage of 60 V at 10% strain and enabling real-time quantitative monitoring of muscle-contraction amplitude and frequency without any external power source.

Simultaneous acquisition of multiparameter physiological signals is an essential requirement for comprehensive assessment of human health status; however, cross-talk between sensing channels for different physical quantities has long constrained the practical accuracy of multimodal sensors. Achieving effective signal decoupling across individual sensing channels constitutes the core design challenge for multifunctional

physiological sensing systems. Kim et al. covalently anchored thermochromic dyes to the inner walls of highly porous electrospun NFs and simultaneously incorporated a CNT conductive network to construct a piezoresistive sensing unit with a sensitivity of 5 kPa^{-1} (Figure 11c) [162], achieving crosstalk-free synchronous acquisition of visualized temperature signals over $30\text{--}45^\circ\text{C}$ and electrical pressure signals while preserving excellent breathability and wearing comfort, effectively resolving the signal-coupling problem inherent to multiparameter sensing.

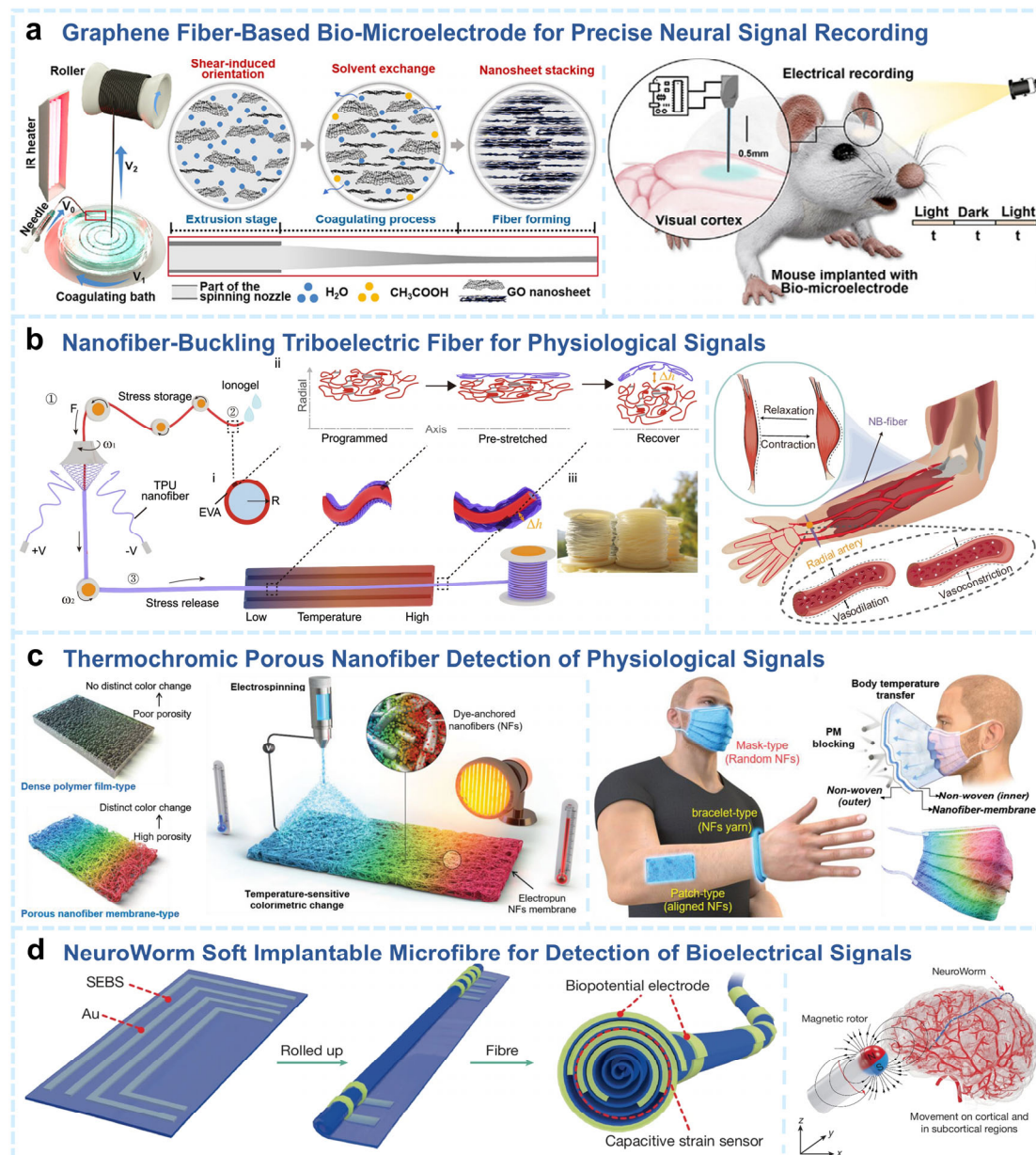


Figure 11. NF-based platforms for biological signal detection. **(a)** Graphene fiber-based bio-microelectrode for precise neural signal recording. Reproduced with permission [160]. Copyright 2026, Wiley-VCH GmbH. **(b)** NF-buckling triboelectric fiber for physiological signals. Reproduced with permission [161]. Copyright 2024, Springer Nature. **(c)** Thermochromic porous NF detection of physiological signals. Reproduced with permission [162]. Copyright 2022, Wiley-VCH GmbH. **(d)** NeuroWorm soft implantable microfiber for detection of bioelectrical signals. Reproduced with permission [163]. Copyright 2025, Springer Nature.

The central challenge of high-density neural interfaces lies in integrating the maximum number of functional electrode channels within an extremely fine fiber form factor while maintaining sufficiently high single-cell signal resolution. Conventional silicon-based neural probes are mechanically rigid and limited in channel density, whereas fiber-form flexible neural interfaces offer a promising technological pathway toward overcoming these bottlenecks. Xie et al. proposed a two-dimensional micromachining-to-three-dimensional rolling transformation strategy (Figure 11d) [163], fabricating a flexible microfiber of $100 \mu\text{m}$ diameter by rolling a planar high-precision electrode array, thereby achieving an ultrahigh integration density of $1024 \text{ channels cm}^{-1}$, *in vivo* experiments

demonstrated stable resolution of more than 200 individual single-unit action potentials, with spatial resolution and signal-to-noise ratio significantly surpassing those of conventional silicon-based neural probes.

4.3. TENG

TENGs, operating on the coupled effects of contact electrification and electrostatic induction, have emerged as core energy-conversion devices for self-powered wearable sensing systems [164–166]. The porous structure, three-dimensional network architecture, and high compliance of NFs can substantially overcome the performance limitations of conventional thin-film-based TENGs across three dimensions, contact area, charge storage, and low-frequency responsiveness, rendering them well suited to the low-frequency, small-amplitude motion characteristic of human-body energy harvesting, and thus constituting an ideal functional material system for high-performance wearable TENGs [167]. Centered on interfacial modification, environmental adaptation, structural design, and green fabrication, NF-based TENGs have undergone multidimensional technological iteration and application expansion.

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Interfacial engineering provides an effective route to enhance triboelectric charge generation and retention in NF-based TENGs. By integrating metal–organic frameworks with electrospun cellulose NFs, a gradient-structured cellulose TENG (CGZT-TENG) was developed through in situ growth of a ZIF-8 nanoshell, surface functionalization, and corona electret treatment (Figure 12a) [168]. The resulting architecture increases the specific surface area by approximately 80-fold, while the MOF pore channels provide spatial confinement that stabilizes electret charges. Consequently, the device delivers an open-circuit voltage exceeding 250 V and a short-circuit current density above 9 mA m⁻², representing a 3–4-fold improvement over pristine cellulose-based TENGs. Beyond charge-generation efficiency, however, practical wearable applications require triboelectric interfaces that remain functional under environmental fluctuations. Addressing this challenge, a superhydrophobic PTFE–SiO₂ NF TENG was constructed by combining nanoparticle-induced hierarchical surface roughness with the intrinsically low surface energy of PTFE (Figure 12b) [32]. The resulting interface exhibits a water contact angle exceeding 160° and retains 87% of its performance at relative humidity above 90%, compared with 21% for conventional devices. Stable operation under rainfall further demonstrates the potential of surface-architecture engineering to mitigate humidity-induced performance degradation.

At the device-architecture level, integrating triboelectric functionality with textile-compatible fiber structures offers another route toward wearable energy harvesting and sensing. In a coaxially electrospun core–shell NF TENG, a silver-coated nylon yarn serves as the conductive core, while a functional polymer shell provides the triboelectric interface (Figure 12c) [169]. This configuration combines electrical conduction and mechanical flexibility within a weavable fiber, enabling the resulting textile to generate voltages exceeding 100 V during ordinary walking. Extending this structural integration toward multifunctional textile systems, a Janus bifacial anisotropic TENG was constructed using TPU and FPU with contrasting triboelectric polarities (Figure 12d) [170]. Their asymmetric arrangement enables contact–separation charge generation within a single-layer textile, while a silver-nanowire network facilitates real-time monitoring of human motion. Incorporation of a degradable PLGA component further introduces an end-of-life biodegradability consideration, linking textile-level sensing functionality with environmental sustainability.

Material selection provides a complementary pathway toward reducing the environmental footprint of NF-based TENGs. In particular, naturally derived cellulose offers a renewable alternative to conventional synthetic triboelectric materials. A bamboo-cellulose NF TENG exploits the intrinsic porosity, flexibility, and degradability of biomass-derived fibers to establish triboelectric contact interfaces without elaborate surface modification (Figure 12e) [171]. This approach highlights the potential of naturally structured fibers for low-cost, sustainable energy harvesting, although their practical performance and scalability must be considered alongside those of engineered polymer systems. Beyond biomass-based materials, incorporating functional nanofillers offers an additional means of tailoring charge storage and dielectric properties. For example, MoS₂ nanosheets were incorporated into a PVA NF network to construct a composite TENG (Figure 12f) [172]. The high dielectric permittivity and layered structure of MoS₂ provide additional opportunities for regulating interfacial charge

generation and trapping, thereby enhancing the triboelectric response of the polymer-based system. Together, these material-level strategies broaden the design space for NF-based TENGs, spanning renewable fiber substrates and functional nanocomposites.

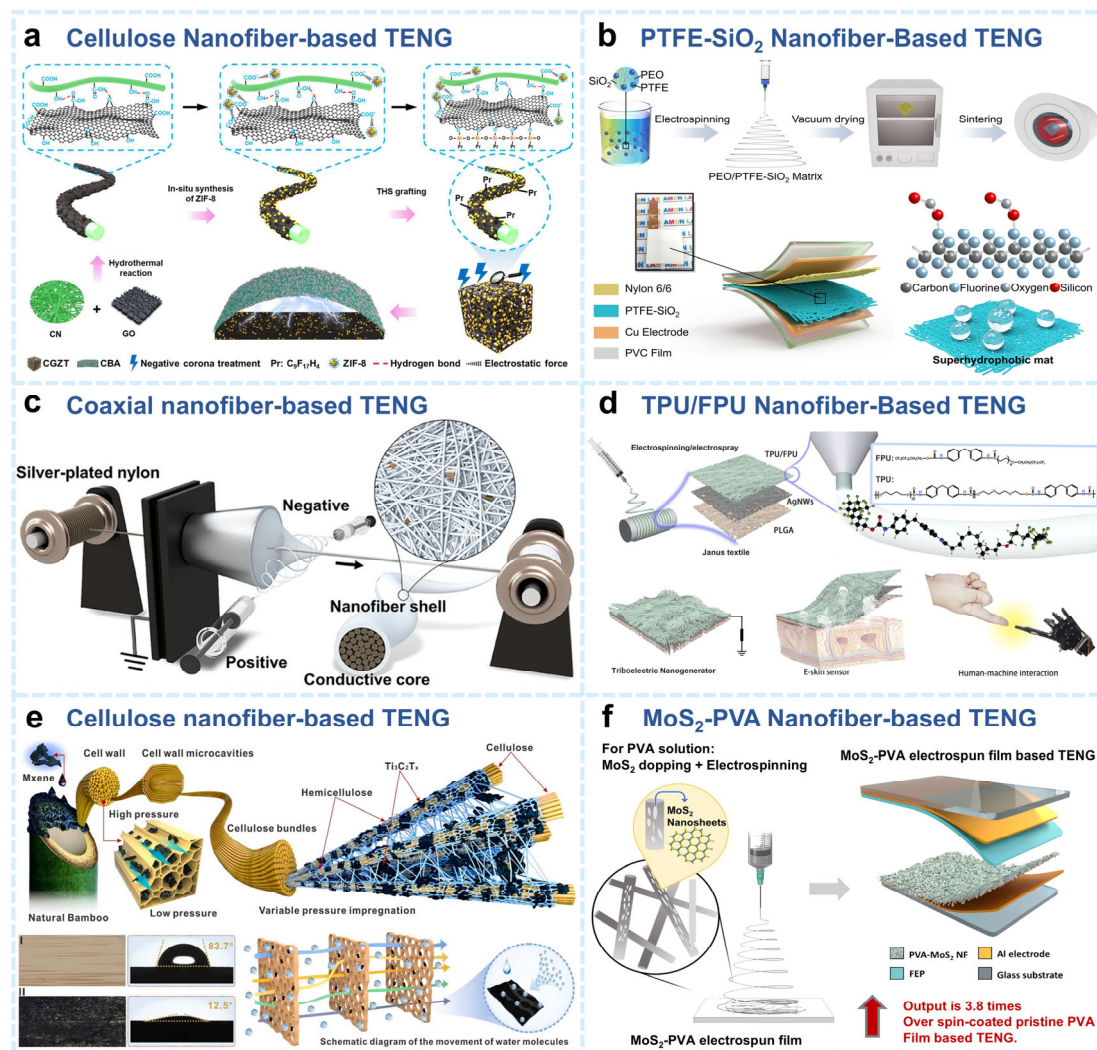


Figure 12. NF-Based TENG device architecture. (a) Cellulose NF-based TENG. Reproduced with permission [168]. Copyright 2024, American Chemical Society. (b) PTFE-SiO₂ NF-based TENG. Reproduced with permission [32]. Copyright 2026, Springer Nature. (c) Coaxial NF-based TENG. Reproduced with permission [169]. Copyright 2026, Wiley-VCH GmbH. (d) TPU/FPU NF-based TENG. Reproduced with permission [170]. Copyright 2025, Elsevier. (e) Cellulose NF-based TENG. Reproduced with permission [171]. Copyright 2023, Elsevier. (f) MoS₂-PVA NF-based TENG. Reproduced with permission [172]. Copyright 2026, OAE Publishing Inc.

4.4. Electrochemistry and Energy Storage

Fiber-based electrochemical energy-storage devices represent both a core shortfall and a critical enabling requirement for constructing fully textile-integrated energy-sensing systems, given that current wearable sensing systems predominantly rely on external rigid batteries for power supply, giving rise to problems of mechanical mismatch, low integration density, and poor wearing experience [173]. Developing in situ fiber-based energy-storage devices to achieve integrated, self-sufficient energy provision at the fabric-platform level constitutes the core development objective for overcoming the limitations of external power supply in wearable systems and realizing true textile-level energy autonomy.

The synergistic co-integration of multimodal energy storage within a single fiber represents an important technological direction for transcending the single-mechanism limitation of conventional fiber energy-storage devices and constructing adaptive energy architectures. Wang et al. integrated three active-material types, LMO, LTP, and AC, in parallel within a single fiber system, combined with gel-electrolyte encapsulation (Figure 13a) [174], simultaneously constructing a lithium-ion fiber battery and two hybrid supercapacitor systems within a single fiber; the device achieves an energy density of 110 Wh kg⁻¹ and a power density of 8500 W kg⁻¹, enabling adaptive

switching between long-duration low-power storage mode and instantaneous high-power output mode according to sensing-application demands, thereby providing a novel device paradigm for intelligent textile energy management.

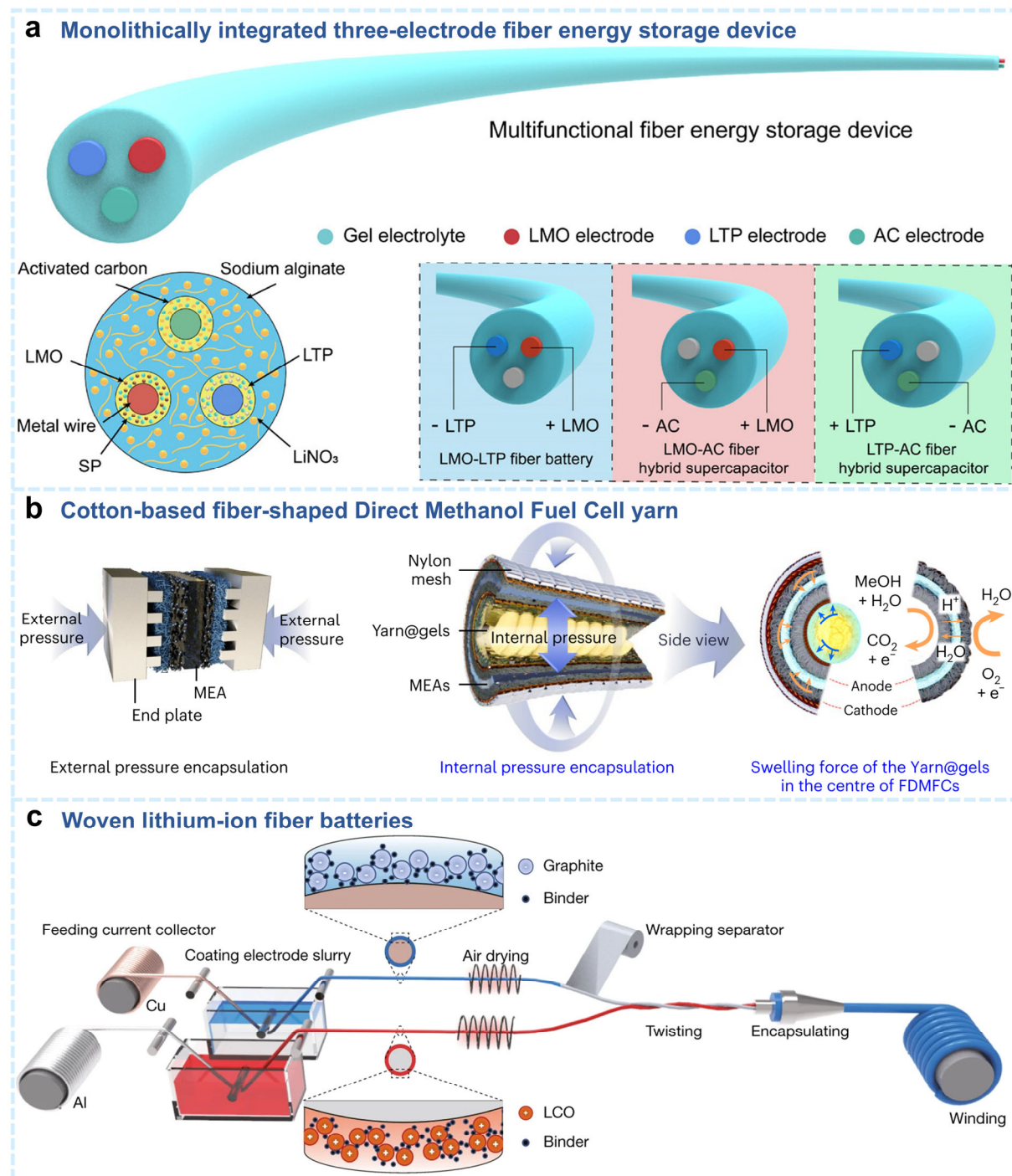


Figure 13. Electrochemical and energy storage applications of electrospun NFs. **(a)** Monolithically integrated three-electrode fiber energy storage device. Reproduced with permission [174]. Copyright 2025, Wiley-VCH GmbH. **(b)** Flexible fiber-shaped fuel cells with gel-mediated internal pressure encapsulation. Reproduced with permission [175]. Copyright 2025, Springer Nature. **(c)** Scalable production of high-performing woven lithium-ion fiber batteries. Reproduced with permission [176]. Copyright 2021, Springer Nature.

Flexible fuel cells offer the combined advantages of high energy density and continuous power delivery; however, maintaining stable interfacial contact pressure and long-term operational reliability without recourse to rigid clamping fixtures constitutes the central bottleneck for their flexible-device implementation. Yuan et al. proposed an internal-pressure self-encapsulation strategy, exploiting the internal stress generated by swelling of a cotton-yarn-gel composite to achieve uniform self-encapsulation of the membrane electrode assembly (Figure 13b) [175], with interfacial contact pressure stably maintained at 0.15 MPa; the resulting fiber fuel cell retains a power density

exceeding 20 mW cm^{-2} under a bending radius below 5 mm, with a continuous operational lifetime exceeding 200 h, providing a reliable engineering pathway toward the practical realization of flexible fuel-cell textiles.

Achieving scalable compatibility between fiber energy-storage devices and the textile industry represents the decisive step in advancing wearable energy-storage systems from laboratory demonstration to practical application. He et al. fabricated a highly stable fiber battery with a linear energy density of 85.69 mWh m^{-1} and a capacity retention exceeding 90.5% after 100 cycles through precisely controlled electrode slurry coating, composite separator construction, and heat-shrink encapsulation (Figure 13c) [176]; this fiber can be directly machine-woven into functional energy-storage textiles and stably power an 8×8 LED array, representing the first substantive realization of the transition from fiber-based energy-storage devices to weavable functional textiles and laying the foundation for the industrial application of integrated wearable energy-sensing systems.

4.5. Human-Machine Interaction

Human-machine interaction (HMI) represents one of the most disruptive application directions for NF-based wearable electronics, aiming to construct a closed-loop information-interaction circuit linking biological sensing with digital systems, mediated through the human body [177]. Relative to conventional rigid HMI devices, NF-based textile platforms offer the distinctive advantages of long-term comfortable wear and unencumbered real-time monitoring, rendering them an ideal medium for achieving continuous, high-precision sensing of human intent and thereby overcoming the inherent application limitations of rigid interactive devices [178]. Leveraging technologies such as fiber-integrated circuits, neural fiber interfaces, and high-precision fiber transfer-printed circuits, NF-based HMI systems have achieved several key breakthroughs, including high-precision gesture recognition, multimodal neural sensing, and visualized motion monitoring.

High-density, multifunctional integration constitutes the central technological challenge for fiber-based HMI systems seeking to transcend the limitations of single-function devices and realize a complete human-machine interaction closed loop. How to simultaneously accommodate sensing, processing, power supply, and display functions within a single fiber while maintaining sufficiently high sensing-node density represents the key scientific and engineering question in this direction. Wang et al. integrated electrochemical power supply, multi-array sensing, transistor-based signal processing (Figure 14a) [179], and organic electroluminescent display units within a composite fiber of 2 mm diameter via a coaxial layer-by-layer helical assembly process, achieving an ultrahigh sensing-node density of $1024 \text{ nodes cm}^{-1}$; a textile HMI glove constructed from this fiber, combined with a convolutional neural network, achieved a recognition accuracy of 97.6% for 26 sign-language gestures, providing a mature system-level solution for intelligent prosthetic control and barrier-free human-machine communication.

Implantable neural interfaces impose stringent and multifaceted requirements on device miniaturization, signal acquisition precision, and biomechanical compliance; achieving simultaneous high-resolution electrophysiological signal recording and real-time tracking of nerve-bundle mechanical deformation at the fiber scale constitutes the central challenge of multimodal neural sensing. Khatib et al. precisely constructed high-resolution electrode arrays and strain-sensing units via a SEBS elastomeric-film micromachining process (Figure 14b) [64], and subsequently fabricated a microfiber device of approximately $100 \mu\text{m}$ diameter, closely matching the dimensions of natural nerve fibers, through axial rolling; this fiber enables synchronous *in vivo* acquisition of single-neuron-resolution electrophysiological signals ($\text{SNR} > 5$) and real-time tracking of nerve-bundle mechanical deformation, providing a novel detection approach for investigating coupled mechano-electrophysiological multimodal neural relationships.

Existing fiber-based electronic circuits have generally struggled to reconcile micro/nanofabrication precision with adaptability to curved fiber substrates, and the efficient, non-destructive integration of high-precision functional circuits onto textile fibers has long remained a fabrication challenge. To address this issue, Jin et al. developed a shrink-transfer-assisted printing process, establishing a universally applicable method for fabricating liquid-metal microcircuits compatible with diverse fiber substrates (Figure 14c) [180]. In this study, buckled liquid-metal microstructures were constructed by pre-stretching an elastomeric substrate, and capillary-force-driven transfer enabled precise printing of the microcircuit, elevating the fiber-surface circuit fabrication precision to $5 \mu\text{m}$. This work overcomes the processing incompatibility between rigid, high-precision microcircuits and flexible curved fiber substrates, providing a generalizable, reproducible, and low-cost fabrication process for high-precision, visualizable fiber-based electronic devices. Following the integration of a luminescent functional layer via this process, the resulting fiber device achieves axially segmented, controllable electroluminescence, enabling intuitive, visualized capture of human gestures and motion states, thereby providing a practically viable technical pathway for the process implementation and application expansion of highly integrated, high-precision textile-based HMI devices.

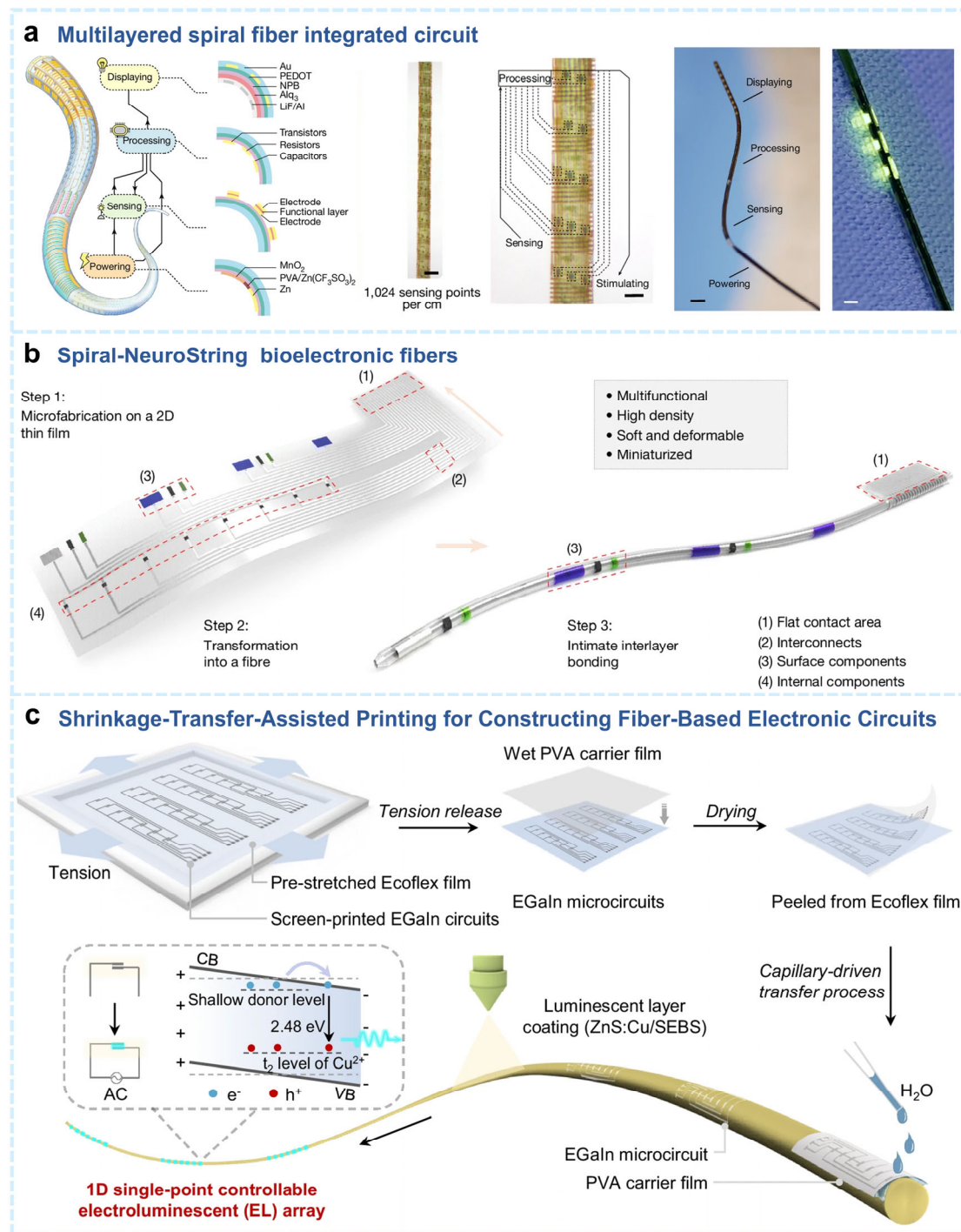


Figure 14. NF-enabled human-machine interaction. (a) Multilayered spiral fiber integrated circuit. Reproduced with permission [179]. Copyright 2026, Springer Nature. (b) Spiral-NeuroString bioelectronic fibers. Reproduced with permission [64]. Copyright 2025, Springer Nature. (c) Shrinkage-Transfer-Assisted Printing for Constructing Fiber-Based Electronic Circuits. Reproduced with permission [180]. Copyright 2026, Springer Nature.

4.6. Multifunctional Protective Wearables

As wearable electronics evolve toward higher integration and longer service life, sensing alone no longer suffices for demanding scenarios such as aerospace, intelligent protection, and long-term health monitoring, where garments must simultaneously provide electromagnetic shielding, thermal management, and mechanical protection. Because these functions are often coupled or even conflicting, research has shifted from optimizing individual conductive materials to multi-scale structural design that decouples them.

In conventional electromagnetic shielding, highly conductive materials predominantly operate via a reflection mechanism, while high shielding effectiveness can be achieved, this approach readily induces secondary electromagnetic pollution. Enhancing electromagnetic wave absorption capability while reducing reflection loss

has therefore become a critical research direction for flexible electromagnetic shielding materials. To address this challenge, Feng et al. constructed CNT@MXene fibers with a gradient conductive architecture via coaxial wet spinning, employing MXene/TPU as the core layer and CNT/TPU as the sheath layer (Figure 15a) [181], by engineering the radial conductivity gradient to promote multiple internal reflections and dissipation of electromagnetic waves within the fiber, an absorption-dominated shielding mechanism ($A = 0.63$) was achieved. The CNT protective layer simultaneously confers excellent environmental stability, maintaining stable electrical conductivity under bending, stretching, and high-humidity conditions. This work demonstrates that gradient conductive structural design is an important strategy for realizing highly efficient absorption-type flexible electromagnetic shielding materials, providing new design concepts for green electromagnetic protective textiles.

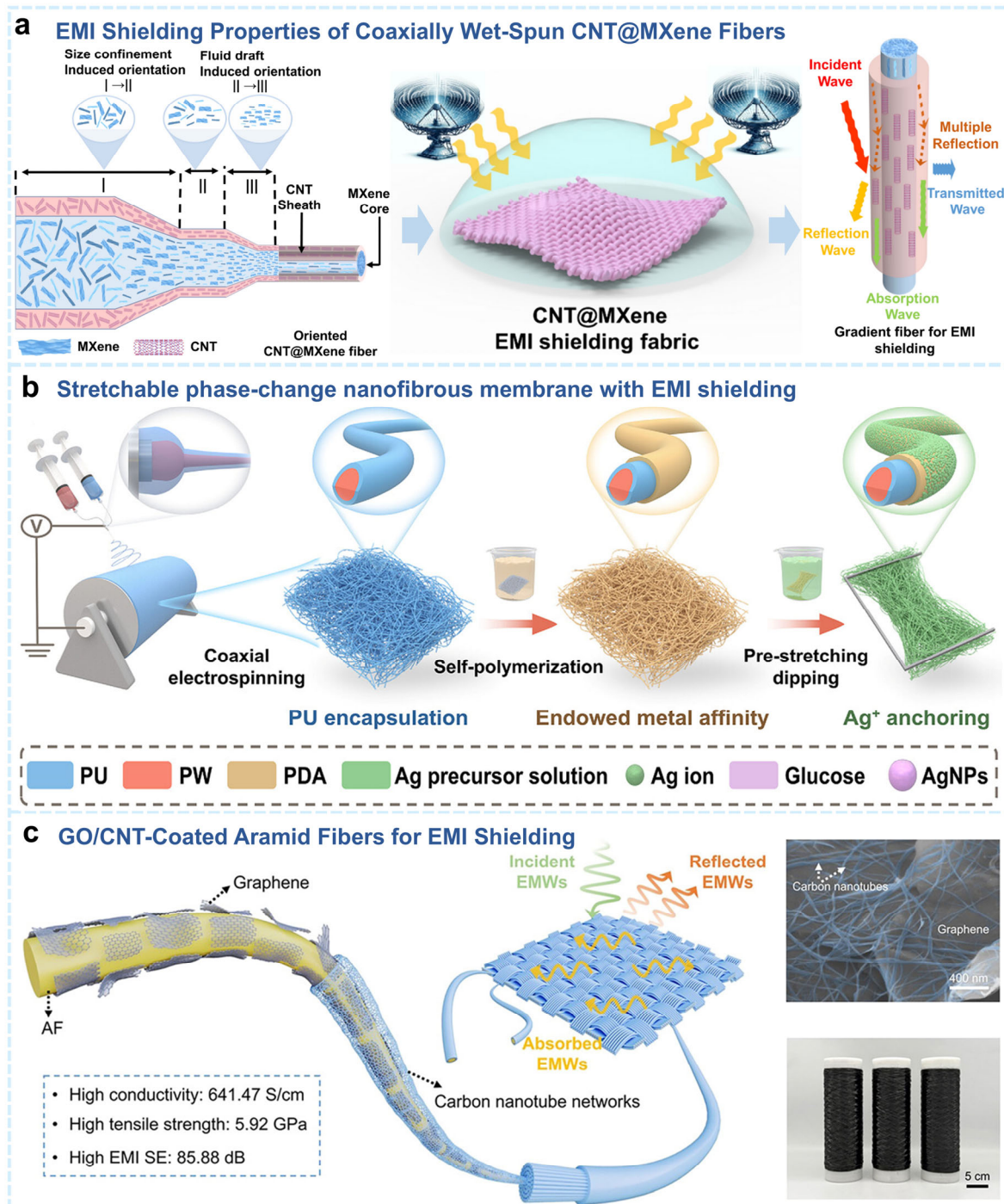


Figure 15. Multifunctional NF Wearable Electronics for EMI Shielding. (a) EMI shielding properties of coaxially wet-spun CNT@MXene fibers. Reproduced with permission [181]. Copyright 2024, Springer Nature. (b) Stretchable phase-change nanofibrous membrane with EMI shielding. Reproduced with permission [182]. Copyright 2026, Wiley-VCH GmbH. (c) GO/CNT-coated aramid fibers for EMI shielding. Reproduced with permission [183]. Copyright 2025, Elsevier.

Beyond electromagnetic protection, human thermal comfort management represents another critical functional requirement for intelligent protective garments. Multifunctional synergistic integration is more aligned with practical wearable scenarios than either thermal management or electromagnetic shielding in isolation. Building on this rationale, Li et al. constructed a stretchable phase-change fiber membrane with a programmable wrinkled conductive network (Figure 15b) [182], using PU/PW core-shell fibers for heat storage and in situ deposited Ag nanoparticles as the conductive layer. The membrane delivers a latent heat of 73.8 J g^{-1} and an initial Shielding effectiveness of 66.4 dB, and combines photothermal conversion, Joule heating, and phase-change storage for dynamic thermal regulation. The wrinkles unfold under stretching to maintain conductive pathways, retaining an SE of 33.71 dB at 100% strain. Although this is a ~49% reduction in dB, it still attenuates over 99.9% of the incident power, well above the ~20 dB generally considered adequate for commercial use. The design nevertheless implies a trade-off in volume allocation between the phase-change component and the conductive layer, while leakage upon repeated melting, cycling stability, and breathability remain to be verified.

Further enhancement of the comprehensive performance of protective textiles depends not only on the introduction of functional materials but, more critically, on the synergistic construction of conductive networks and high-performance fiber matrices. To address the challenge of achieving uniform assembly of carbon-based nanomaterials on fiber surfaces, Liu et al. proposed a sequential assembly strategy based on dimensional engineering (Figure 15c) [183], exploiting the complementary geometries of two-dimensional graphene and one-dimensional carbon nanotubes: graphene offers large-area coverage, whereas nanotubes bridge the gaps between sheets, forming a continuous, dense heterogeneous network on aramid fibers. The composite fiber reaches a conductivity of 641.47 S cm^{-1} , a tensile strength of 5.92 GPa, and an SE of 85.88 dB. The aramid core thus bears the load while the carbon network governs conduction and shielding, effectively decoupling the mechanical and electromagnetic functions. Whether this decoupling persists under repeated bending, abrasion, and laundering, however, warrants further validation.

Taken together, multifunctional protective wearable devices are progressively evolving from single conductive fibers toward intelligent textile platforms that integrate electromagnetic shielding, thermal management, mechanical reinforcement, and environmental stability. Gradient conductive architectures, multi-dimensional heterogeneous conductive networks, and multifunctional synergistic integration have emerged as core design strategies for enhancing comprehensive protective performance, and will constitute important development directions for next-generation intelligent protective wearable systems.

4.7. Textiles-Integrated Wearable Electronics

E-textiles achieve deep integration of wearable electronics with the textile system by embedding functional devices within the fabric itself [184]. Relative to conventional patch-type wearable devices, textile-integrated designs fundamentally eliminate interfacial mechanical mismatch, reconciling device functionality with the intrinsic flexibility, breathability, and comfort of textiles, and thus represent a core development direction for next-generation wearable technology [185]. To date, textile-integrated electronics have achieved a number of representative breakthroughs in wireless sensing, fiber-based microelectronics, and breathable tactile sensing.

Conventional wearable textile electronics rely on rigid chips, external antennas, and high-power-consumption wireless modules, rendering native wireless textile sensing difficult to achieve; the inherent conflict between wireless capability and mechanical flexibility constitutes the central bottleneck constraining the practical deployment of electronic textiles. Yang et al. creatively employed the human body itself as a natural (Figure 16a) [186], low-loss radiofrequency transmission medium, exploiting fiber-skin capacitive coupling to circumvent dependence on rigid wireless modules such as Bluetooth and Wi-Fi, thereby constructing a native wireless textile-sensing architecture free of rigid chips, the system integrates sensing, antenna, and display fibers to synchronously monitor multimodal physiological signals, including heart rate, gait, and skin temperature, during human motion, achieving a wireless transmission distance of 1.5 m at a power consumption of only approximately 2 mW.

Functional fibers have long been constrained to single-function modification and cannot integrate systematized microelectronic functionality at the single-fiber scale, representing a critical technological barrier to the evolution of fiber-based electronic devices toward complete systems. Hwang et al. proposed a “fiber-chip” strategy (Figure 16b) [187], integrating complete microelectronic units, including thin-film transistors, ultraviolet sensors, and ring oscillators, on the surface of an ultrafine electronic fiber with a diameter of $150 \text{ }\mu\text{m}$ via micro/nanofabrication techniques such as atomic layer deposition and precision patterned deposition, constructing a fully functional single-fiber electronic system; this electronic fiber can be embedded into commercial textiles through conventional weaving processes and exhibits no discernible functional degradation after ten thousand bending cycles and more than twenty machine-wash cycles.

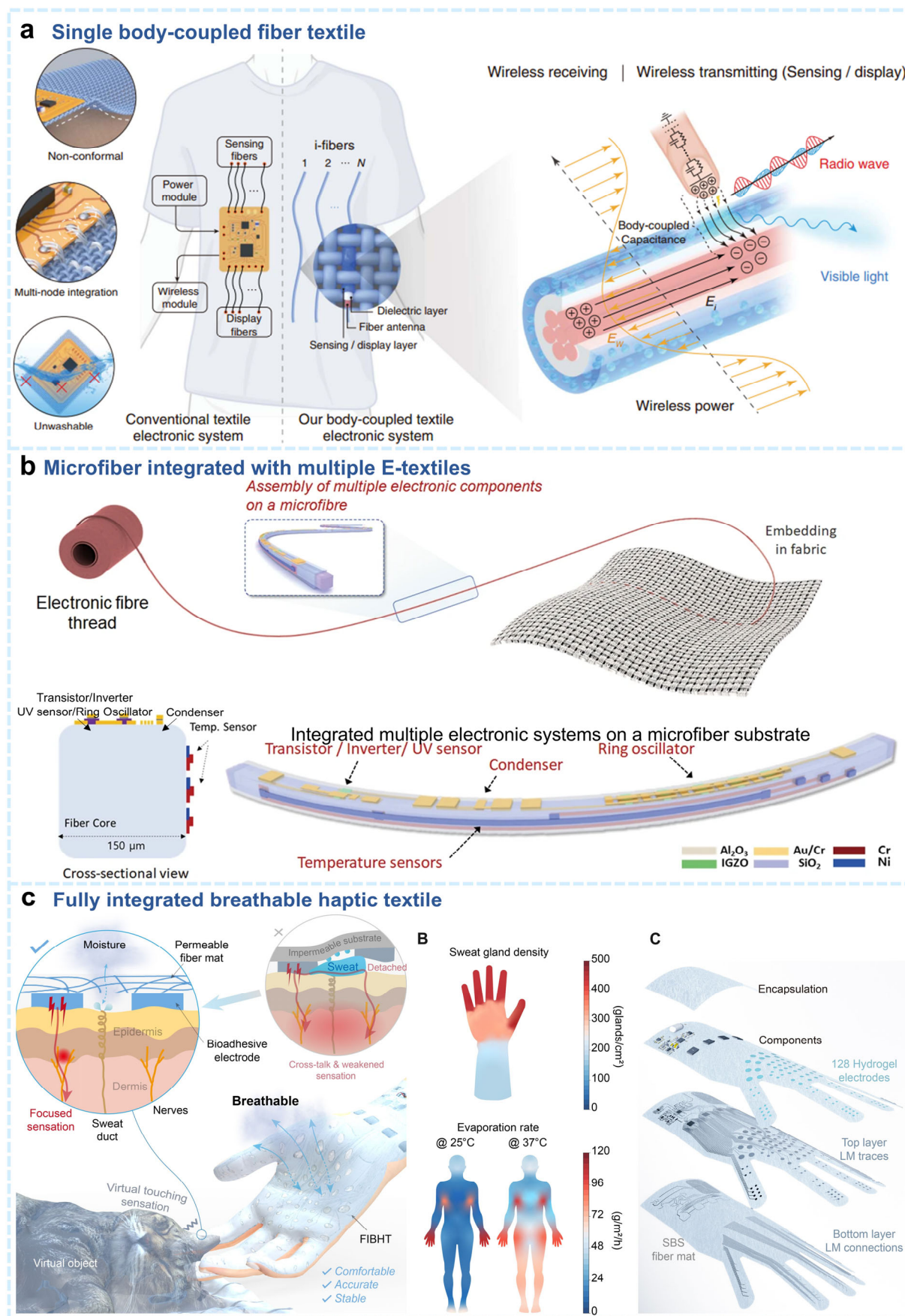


Figure 16. Textiles-integrated electronic textiles for intelligent wearable electronics. **(a)** Single body-coupled fiber textile. Reproduced with permission [186]. Copyright 2024, American Association for the Advancement of Science. **(b)** Microfiber integrated with multiple E-textiles. Reproduced with permission [187]. Copyright 2022, Springer Nature. **(c)** Fully integrated breathable haptic textile. Reproduced with permission [188]. Copyright 2024, American Association for the Advancement of Science.

Existing tactile-sensing textiles universally suffer from poor breathability, low channel density, and difficulty in reconciling multiple functionalities, falling short of the demands of high-precision human–machine interaction and clinical detection. Achieving high-density, multimodal synchronous acquisition of tactile and electrophysiological signals while preserving textile wearing comfort constitutes the central challenge in this direction. Yao et al. constructed a three-layer composite functional architecture comprising a breathable substrate (Figure 16c) [188], conductive wiring, and a high-density electrode array, with a porous SBS fibrous substrate ensuring breathability at a moisture-evaporation transmission rate 3.2 times that of conventional liquid-metal-based substrates; combined with a 128-channel high-density hydrogel electrode array, the system achieves ultrahigh spatial-resolution potential mapping at 3 mm and an ultralow tactile-detection threshold of 5 mN, enabling synchronous capture of palmar tactile distribution, fingertip electromyographic signals, and skin temperature-field distribution, conferring significant application value in neuroprosthetic tactile feedback and precision human–machine interaction.

5. Conclusions and Future Perspectives

This review has summarized recent progress in electrospun-NF-based wearable electronic devices, encompassing the jet-formation mechanisms underlying electrospinning, the regulation of fiber microstructure, the construction of functional material systems, and their applications in textile-integrated sensing, energy harvesting, electrochemical energy storage, and human–machine interaction. Owing to their high specific surface area, tunable porous structure, excellent mechanical flexibility, and favorable conformability, electrospun NFs have emerged as core material platform for next-generation wearable devices [68]. However, most devices remain at the proof-of-concept stage, with precise control over fiber architectures, batch-to-batch process reproducibility, long-term operational reliability, and system-level integration continuing to pose major challenges to practical deployment. These bottlenecks are interdependent, propagating from materials design through process scale-up to device reliability and system integration. This section examines the challenges and future directions across six dimensions: material structural design, scalable fabrication, green and sustainable processing, device practicality and reliability, intelligent manufacturing, and self-powered wireless integration.

5.1. NF Structural Design and Structure–Property Relationships

The precise fabrication of high-performance electrospun NFs depends fundamentally on the rational design of the spinning system. The thermodynamic compatibility and rheological synergy among the polymer matrix, solvent system, and functional additives directly determine the microscale morphology, structural uniformity, and formation stability of the resulting NFs (Figure 17a) [189]. Hansen solubility parameters (δ_D , δ_P , and δ_H) provide a basis for solvent selection in single-component systems. However, in the development of multifunctional NFs, the incorporation of metal salt precursors, carbon-based nanomaterials, and inorganic fillers simultaneously alters solution viscosity, electrical conductivity, surface tension, and phase-separation kinetics. These coupled effects limit the ability of equilibrium-based descriptors to adequately capture the behavior of multicomponent systems, substantially complicating their precise control [190]. Taking piezoelectric PVDF as an example, the β -phase content, and consequently the piezoelectric output, is jointly governed by solvent polarity, jet stretching, and post-treatment conditions, reflecting the strong coupling among processing parameters. The intricate relationships linking fiber composition and microstructure to the electrical, mechanical, and sensing performance of devices span multiple length scales, from molecules and individual fibers to fibrous membranes and integrated devices. A systematic and quantitative structure–property relationship framework remains lacking. Consequently, conventional trial-and-error approaches based on single-variable optimization are ill-suited to the simultaneous optimization of multiple interdependent parameters, often resulting in structural heterogeneity, poor dispersion of functional components, and insufficient device reproducibility. Future efforts should therefore begin with standardized characterization of spinning solutions (polymer molecular weight and concentration, viscosity, conductivity, surface tension, and ambient temperature and humidity) to generate comparable datasets for quantitative modeling. On this basis, multiscale molecular dynamics simulations, first-principles calculations, and machine-learning methods—can be integrated to construct a composition–structure–performance model that elucidates the mechanisms governing complex composite systems. Given the limited experimental data typically available, Bayesian optimization and active learning can approach the optimal processing window with fewer experimental iterations, while interpretable models can extract physical insight rather than merely providing black-box predictions. Together, these approaches will enable the inverse design and performance-directed optimization of functional NFs.

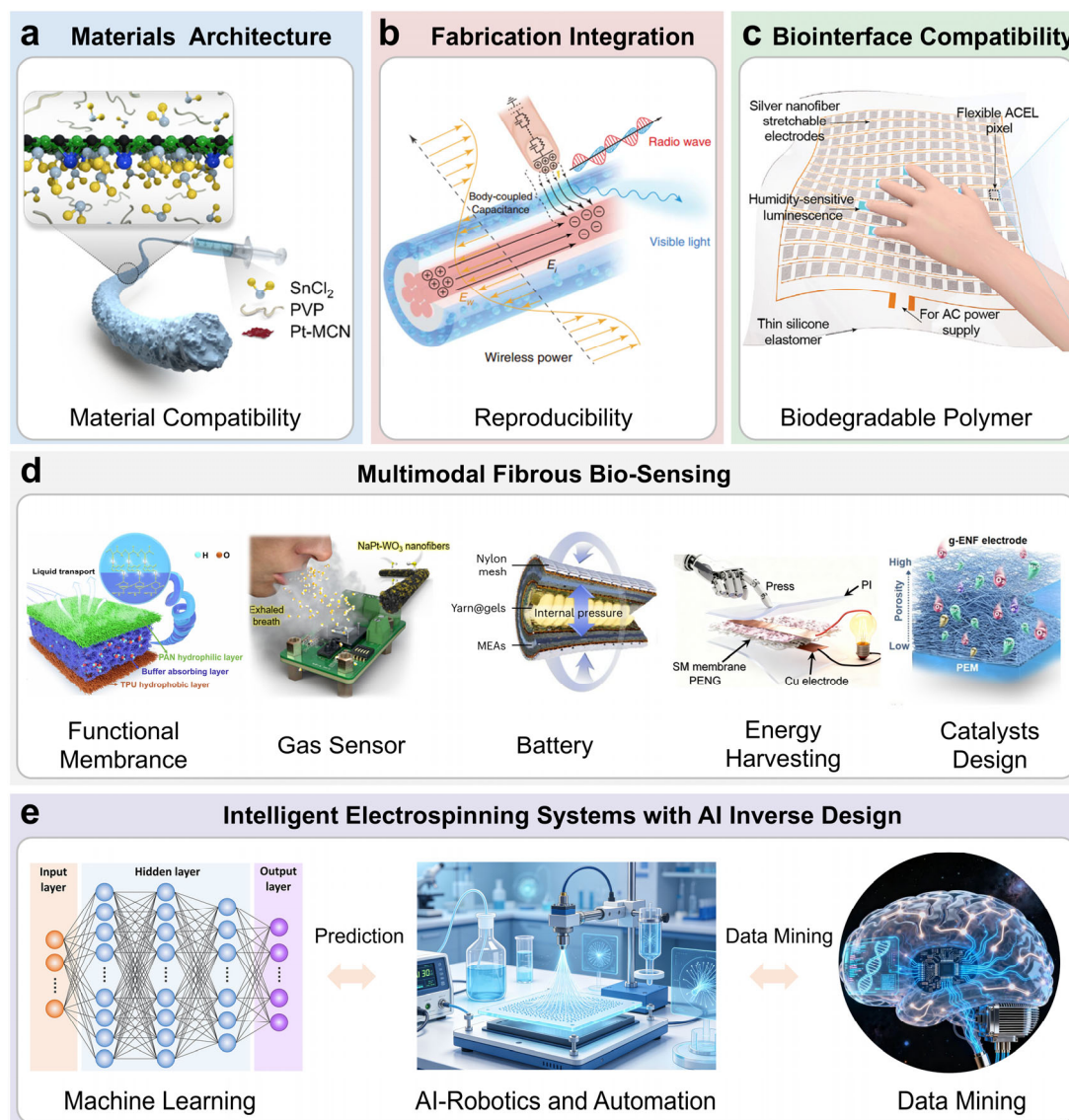


Figure 17. A comprehensive outlook for NFs toward wearable electronics. **(a)** Materials architecture and compatibility of multicomponent electrospun NFs. Reproduced with permission [129]. Copyright 2020, American Chemical Society. **(b)** Reproducible fabrication and device-level integration. Reproduced with permission [186]. Copyright 2024, American Association for the Advancement of Science. **(c)** Biocompatible, skin-conformal NF interfaces. **(d)** Multimodal fibrous platforms: functional membranes Reproduced with permission [189]. Copyright 2025, Springer Nature; gas sensors. Reproduced with permission [191]. Copyright 2021, American Chemical Society; batteries. Reproduced with permission [175]. Copyright 2026, Wiley-VCH GmbH; energy harvesters and catalysts. **(e)** Intelligent electrospinning with AI inverse design, combining machine learning, robotic automation and data mining.

5.2. Process Stability in Scalable Fabrication

The product consistency and industrial scalability of electrospun NFs depend critically on the stable control of processing parameters and environmental conditions. Core processing parameters, including spinning voltage, solution feed rate, collection distance, and collector-substrate translation speed, together with external conditions such as ambient temperature, humidity, and airflow disturbance, directly influence the solvent evaporation rate, solution conductivity, and jet-stretching behavior, and can readily give rise to nonuniform fiber diameter, variable membrane thickness, and an increased density of structural defects (Figure 17b) [192]. Furthermore, conventional single-needle electrospinning systems typically operate at feed rates of only 0.1–1 mL h⁻¹, limiting production throughput. Although multi-needle arrays can increase productivity, electrostatic interference between adjacent jets can compromise membrane thickness uniformity. Needleless electrospinning, in turn, is often associated with stochastic jet initiation and broader fiber diameter distributions, while conventional static, batch-based processes cannot continuously produce large-area fibrous membranes. Consequently, the outstanding performance

demonstrated at the laboratory scale is often difficult to reproduce consistently in scaled-up manufacturing. To bridge this gap, future research should develop intelligent, continuous roll-to-roll electrospinning systems. Such systems should (i) optimize spinneret configurations through electric-field simulations and maintain a controlled, enclosed spinning environment with regulated temperature and humidity; and (ii) integrate optical morphology characterization and machine vision to monitor Taylor cone dynamics, fiber orientation, pore-size distributions, and membrane integrity in real time, with closed-loop feedback to dynamically compensate for process drift. Continuous collection should also be coupled with in-line post-treatments, such as hot pressing, poling, and lamination, to convert as-spun membranes into device-grade materials. In parallel, a standardized quality assessment framework should be established based on fiber diameter distribution, membrane thickness uniformity, defect density, and batch-to-batch variability, thereby enabling comparable and reproducible manufacturing across laboratories and production lines.

5.3. Green and Sustainable Fabrication Processes

Traditional electrospinning relies heavily on highly volatile organic solvents such as N,N-dimethylformamide and N-methyl-2-pyrrolidone, both of which are associated with reproductive toxicity and are subject to regulatory scrutiny under frameworks such as the EU REACH regulation. Solvent volatilization poses environmental and occupational health risks, while residual solvents can compromise fiber biocompatibility and undermine the long-term stability of devices (Figure 17c) [193]. Meanwhile, widely used polymers such as PVDF and polyacrylonitrile are resistant to biodegradation, raising concerns over microplastic pollution from discarded devices and creating a fundamental tension with the sustainability goals of wearable electronics [194]. To address these issues, green, low-toxicity, and biodegradable process development represents an important future direction. On one hand, green spinning processes employing aqueous-phase systems or low-toxicity bio-based solvents as the processing medium must be developed, eliminating environmental pollution and solvent-residue risks at their source; on the other hand, the engineering-scale application of naturally degradable polymers such as cellulose, chitosan, silk fibroin, and poly(lactic acid) should be advanced, thereby fundamentally resolving the problem of secondary pollution arising from device disposal and promoting environmentally friendly practices throughout the full life cycle of NF materials.

5.4. Enhancement of Device Practicality and Reliability

Although electrospun NFs have demonstrated considerable potential across multiple wearable application directions, devices largely remain confined to laboratory-scale validation, and each applications faces distinct bottlenecks. In the domain of physiological sensing, sweat-induced corrosion, interfacial delamination, and motion artifacts undermine long-term signal stability; in the domain of energy harvesting and storage, devices continue to suffer from limited cycling lifetime, poor environmental tolerance, and low integration density; and in the domain of human-machine interaction, large-scale array integration remains challenging, with insufficient precision in multimodal signal decoupling (Figure 17d) [195]. Furthermore, the absence of standardized evaluation frameworks for device biosafety, washing durability, and mechanical longevity impedes clinical translation and commercialization. To address these limitations, application-specific strategies are needed: physiological-monitoring applications should prioritize skin-interface compatibility, through hydrophobic-hydrophilic gradients or biomimetic adhesive layers, and resistance to motion interference, through breathable encapsulation, strain-isolation structures, and adaptive filtering or deep-learning-based denoising; energy-system applications should improve environmental tolerance and cycling stability, while pairing harvesters with efficient impedance-matching and power-management circuits to build integrated energy-sensing platforms; and human-machine interaction applications should refine multimodal signal-decoupling algorithms and high-density array-integration processes. Concurrently, existing standards, including ISO 6330 [196] for domestic laundering, ISO 105-E04 [197] for colorfastness to perspiration, and ISO 10993 [198] for biocompatibility, should be leveraged to establish unified evaluation protocols encompassing washing durability, bending/tensile cycling stability, perspiration resistance, and biosafety. Such standardized assessment frameworks are essential for bridging the translational gap between proof-of-concept demonstrations and clinical or commercial deployment.

5.5. Intelligent Manufacturing and AI-Assisted Design

Conventional electrospinning relies on empirical regulation and iterative trial-and-error, resulting in low research and development efficiency. Moreover, existing platforms are generally capable of fabricating only simple planar fibrous membranes, which cannot meet the demands of three-dimensional, gradient-functional, or skin- and textile-conformal devices required by next-generation integrated wearable electronics (Figure 17e) [199].

The deep integration of artificial intelligence with robotic technology offers a practical pathway toward overcoming these bottlenecks. Machine-learning-based predictive models can establish quantitative structure–property relationships among spinning parameters, fiber structure, and device performance, enabling inverse parameter optimization directed toward target performance outcomes and shortening the research and development cycle [200]. Multi-degree-of-freedom robotic spinning platforms can overcome the limitations inherent to conventional two-dimensional fabrication, enabling programmable, precise manufacturing of three-dimensionally structured NF devices. Integrating automated formulation, in-line characterization, model updating, and robotic forming into self-driving laboratories, supported by digital twins for process prediction, will drive a transformation in NF device fabrication, from empirical trial-and-error toward a data-driven paradigm. A prerequisite for this transition is the establishment of standardized, shareable, high-quality process databases, which remain a critical gap.

5.6. Self-Powered and Wireless Wearable Systems

Despite the advances achieved in the sensing performance of electrospun NF-based wearable electronics, the majority of devices continue to rely on external power sources, rigid electronic modules, and wired connections, which constrain long-term wearing comfort and practical deployment, particularly in scenarios demanding imperceptible integration, such as sleep monitoring and continuous health surveillance. Triboelectric, piezoelectric, and thermoelectric energy harvesters based on electrospun NFs can scavenge ambient energy from human motion, respiration, and body heat, offering a promising route toward self-powered flexible electronics. However, their practical deployment remains constrained by several fundamental limitations: the output power of these devices is typically insufficient to sustain continuous operation of wireless modules; thermoelectric harvesters are intrinsically limited by the small temperature differences of only a few kelvin between the human body and its surroundings; and the high output impedance of triboelectric generators complicates efficient electrical matching with downstream power-management circuits. The deep convergence of self-powered technologies with wireless communication will therefore constitute a critical development direction toward autonomous wearable systems. Triboelectric, piezoelectric, and thermoelectric energy harvesters constructed from electrospun NFs can fully exploit ambient energy sources inherent to the human body, such as motion, respiration, and body heat, to provide continuous power supply for flexible electronics; combined with low-power wireless communication technologies, real-time transmission of physiological signals can be realized, further liberating devices from dependence on external power sources and wired connections. Looking ahead, through the integration of energy harvesting, sensing, wireless communication, and intelligent data processing within a unified platform, electrospun NF-based wearable electronics are poised to advance toward lightweight, wireless, and autonomous configurations, providing more reliable technological support for long-term health monitoring, digital medicine, and intelligent health management.

In summary, electrospun NF-based wearable electronics are entering a critical stage of rapid performance evolution and technological translation. Progress will depend less on optimizing individual performance metrics than on addressing the common challenges of predictive structure–property models, scalable manufacturing, material sustainability, long-term device reliability, and self-powered wireless integration. With the concerted development of precision fiber design, green and scalable fabrication, durable biointerface engineering, and intelligent manufacturing, NF-based materials are poised to enable broader applications in emerging fields such as intelligent health monitoring, neurorehabilitation and diagnosis, and human–machine interaction, providing a robust materials foundation for next-generation flexible wearable electronic systems.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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