

Bioinspired helical nanofibrous architectures for functional devices: From formation mechanisms to multifunctional applications

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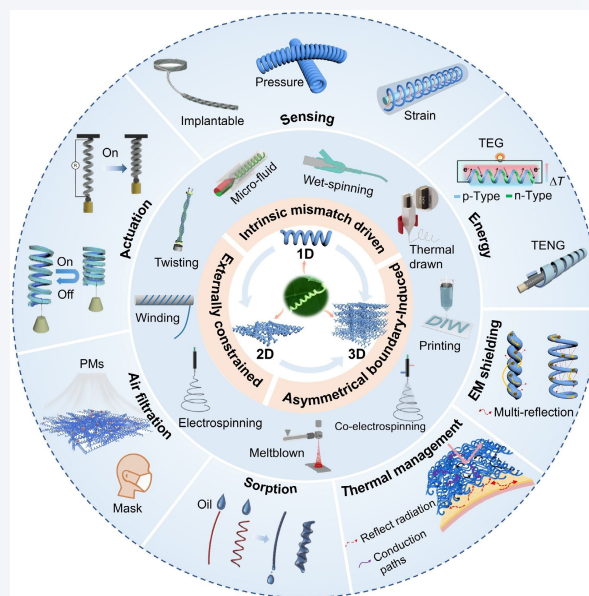
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ABSTRACT: Helix-enabled advanced fibrous devices are emerging as a powerful multidisciplinary platform for next-generation soft systems, enabling robust functionality under complex mechanical and environmental conditions. Compared with conventional straight-fiber or planar architectures, helical geometries offer high mechanical compliance, large elastic deformability, and geometry-amplified responses. Meanwhile, their hierarchical pore networks and enlarged specific surface area provide additional leverage for regulating mass/heat/electromagnetic transport. In this review, we systematically summarize state-of-the-art progress in helix-enabled fibrous devices across multiple length scales, spanning one-dimensional (1D) helical fibers, two-dimensional (2D) helical fibrous membranes, and three-dimensional (3D) fluffy assemblies. We first clarify helix-formation mechanisms, structure design principles, and representative fabrication strategies, and then highlight broad applications in soft sensing, actuation, energy management, filtration and separation, thermal management, and microwave absorption. Finally, we outline key challenges and opportunities, emphasizing sustainable material platforms, programmable structural control and scalable manufacturing, quantitative structure-property relationships, real-world reliability, and coherent multifunctional integration, aiming to guide the rational design and translation of next-generation helix-enabled fibrous technologies.

KEYWORDS: bio-inspired, helical fibers, fluffy, spinning, wearable devices



1 Introduction

The helix, as a fundamental form of curvature, represents an efficient structural strategy to accommodate extended length and mechanical compliance within spatially confined environments [1].

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In nature, helical architectures are ubiquitous, spanning plant tendrils, bacterial flagella, DNA molecules, spider silks, and muscle fibers [2–4]. Such three-dimensional coiled geometries endow biological systems with functionalities that are difficult to achieve using linear or planar structures. On one hand, the spring-like configuration provides exceptional elasticity, stretchability, and energy-buffering capability, enabling structures such as tendrils to withstand strong winds and external impacts while preserving structural integrity [5, 6]. On the other hand, the intrinsically curved three-dimensional (3D) morphology increases the specific surface area and generates hierarchical porous networks, facilitating efficient light capture, moisture absorption, mass transport, and spatial growth [7–9]. Together, these mechanical and

morphological advantages make helicity a highly optimized natural design principle for multifunctional performance.

Inspired by these intrinsic merits, extensive efforts have been devoted to engineering bioinspired helical fiber-based devices via diverse fabrication routes, including spinning induced self-coiling [10–12], twisting-enabled coiling and supercoiling [13], and winding-assisted assembly [14, 15]. This body of research has evolved along two complementary directions. First, leveraging geometry-dominated deformability and strain accommodation, one-dimensional (1D) helical fibers have been developed into stretchable and wearable electronics, such as strain sensors, soft actuators, and energy-related devices, where helical uncoiling can amplify signal transduction while maintaining mechanical stability and robustness. Second, researchers have leveraged helix-induced high surface area and interconnected porous architectures to construct highly porous two-dimensional (2D) membranes and 3D fluffy assemblies, enabling improved performance in filtration and separation, thermal management, and microwave absorption. These advances demonstrate that helical architectures offer not merely geometric novelty, but a powerful structural platform to overcome key limitations of conventional straight or planar fibrous devices.

Despite rapid progress, existing review articles predominantly focus on 1D helical fiber devices [26–28], while 2D membrane- and 3D assembly-level helical architectures are under-represented and comprehensive cross-dimension reviews spanning 1D fibers to 3D assemblies remain scarce. Moreover, the formation mechanisms governing cross-dimension helical fibrous devices have not been organized into a unified framework. In this review, we address these gaps by establishing a unified framework for helix formation. Specifically, we classify formation mechanisms into three categories, namely intrinsic mismatch, interfacial compression induced, and external constraints, and summarize the corresponding design principles and fabrication strategies across length scales (Fig. 1). We further provide an integrated overview of multifunctional applications. We first summarize 1D helical fibers for wearable electronics and implantable bioelectronics and clarify how their unique mechanics enable performance enhancement. Specifically, the helical fibers covered in this review mainly include carbon-based helical fibers (e.g., helical carbon fibers and CNT bundles), inorganic/metallic helical nanostructures (e.g., ZnO nanobelts), and polymer-based helical fibers (e.g., TPU- and PEG-based systems) [29]. We then review 2D helical fibrous membranes for filtration and separation, highlighting pore structure-driven efficiency and resistance trade-offs. Finally, we discuss 3D helical assemblies for thermal management and microwave absorption, emphasizing the role of 3D pore architectures in heat-transfer suppression and wave dissipation. We conclude by outlining remaining challenges and future opportunities, including programmable structural control, scalable manufacturing, and coherent multifunctional integration, aiming to guide the rational design and translation of next-generation helical fibrous devices and to stimulate technological breakthroughs in this rapidly evolving field.

2 Formation mechanisms of helical structure

Helical formation is an energetically favorable outcome of a material system under specific internal or external constraints, and can be broadly understood as the synergy between mechanical instability and energy minimization. When a system contains stress

gradients or is subjected to incompatible deformations, uniform strain accommodation often becomes energetically prohibitive. Instead, the material breaks symmetry and relaxes through geometric curling into a new equilibrium state. In this process, helicity acts both as a stress distributor, converting macroscopic loading into periodic local deformation to mitigate stress concentration, and as a strain amplifier, transforming small axial deformation into pronounced geometric displacement. Based on the driving origin and constraint conditions, helical formation mechanisms can be categorized into three classes: intrinsic mismatch driven, interfacial compression induced, and externally constrained mechanisms.

2.1 Strain-induced curvature in the bilayer

Intrinsic mismatch driven helicity originates from internal strain gradients generated by dissimilar material responses within a composite or architected system (Fig. 2(a)). Depending on the mismatch source, this class can be further divided into mechanically induced mismatch, thermal-expansion mismatch, and photo-response mismatch. Beyond these cases, molecular-level symmetry breaking, for example through chiral molecular assembly or helical dislocation-driven growth, also represents a distinctive pathway for generating helical fibrous structures [29].

2.1.1 Mechanical mismatch induced helicity

A direct and widely used route is the “pre-stretch, bond, and release” strategy, which mechanically couples an energy-storing elastomeric substrate with a passive constraint layer. For example, functional conductive layers can be bonded onto pre-stretched elastomeric fibers (e.g., silicone or Ecoflex) to realize such architectures [20, 31]. Upon release, elastic retraction is constrained by the non-stretchable functional layer, forcing the system to break symmetry and buckle into a helical configuration to minimize total strain energy. In addition to post-bonding routes, bicomponent electrospinning enables one-step fabrication of helical fibers [11]. Helicity emerges from the dynamic competition between strong electrostatic drawing and component-specific viscoelastic responses. In side-by-side configurations, asynchronous elongation of the two components along the whipping trajectory accumulates a relative strain mismatch. After deposition and tension release, this stored mismatch relaxes into an equilibrium helical geometry (Fig. 2(b)).

2.1.2 Thermal-expansion mismatch induced helicity

Helical formation can also be driven by mismatched coefficients of thermal expansion (CTE) or thermally induced shrinkage between bonded layers or components (Fig. 2(c)). Under heating or cooling, differential expansion generates internal bending and twisting moments. When bending and torsional energies compete, the system may adopt a helical configuration rather than a simple planar curvature [23]. Such thermally driven mismatch is particularly relevant for bilayer or core-sheath fibers in which one component exhibits significantly higher CTE or temperature-dependent softening, enabling programmable temperature-responsive coiling and reversible morphing.

2.1.3 Photo-response mismatch induced helicity

Light-responsive helicity typically arises when one component undergoes photo-induced contraction or crosslinking while the other remains relatively inert (Fig. 2(d)). The resulting differential natural length creates an internal moment that drives curling and

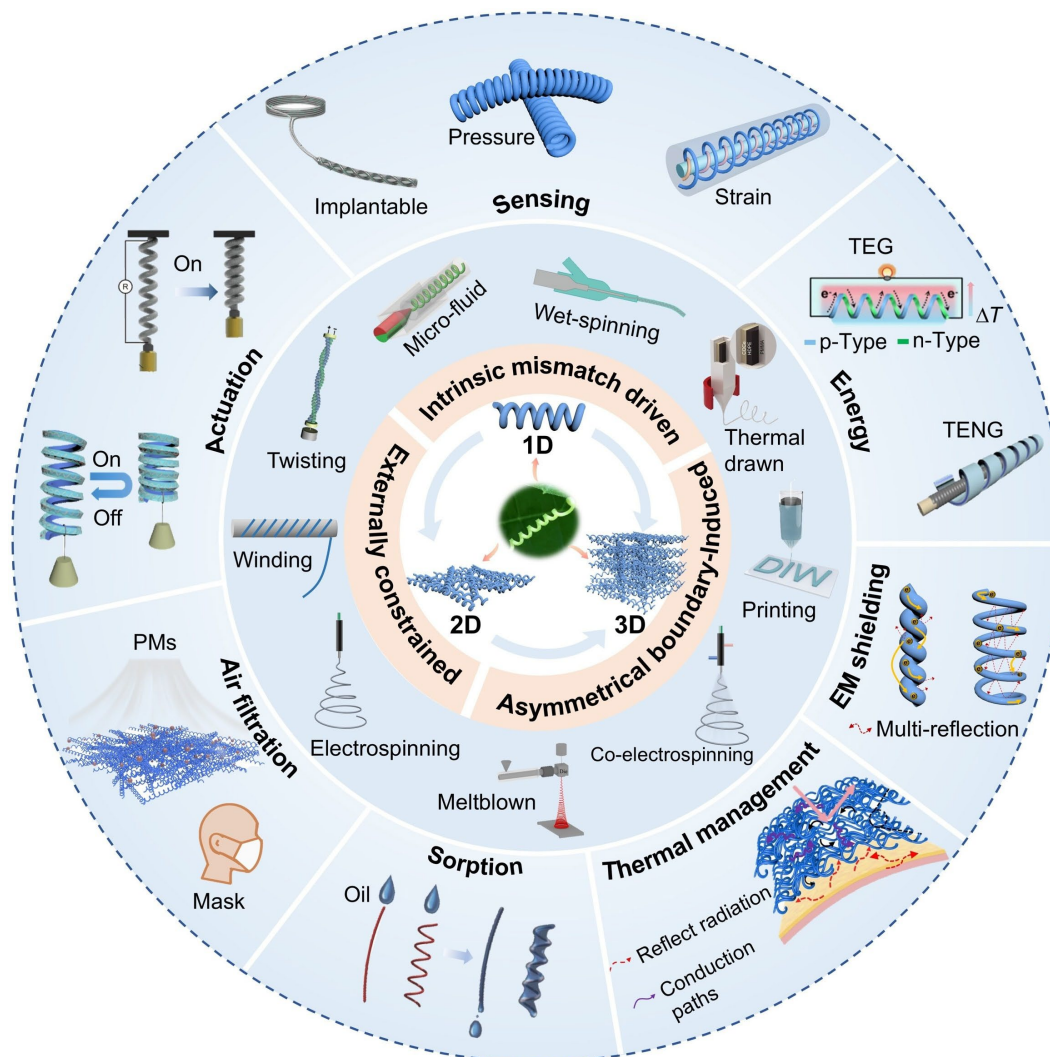


Figure 1 Overview of the formation mechanisms, fabrication strategies, and diverse applications of full-scale helical fibrous architectures (spanning 1D fibers, 2D membranes, and 3D assemblies). Reproduced with permission from Ref. [9], © American Chemical Society 2024; Ref. [16], © Elsevier Ltd. 2024; Ref. [17], © Elsevier Ltd. 2022; Ref. [18], © American Chemical Society 2025; Ref. [19], © Donghua University, Shanghai, China 2024; Ref. [20], © American Chemical Society 2018; Ref. [21], © Noh, S. et al. 2024. Small published by Wiley-VCH GmbH; Ref. [22], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2017; Ref. [23], © Kanik, M. et al. 2019, some rights reserved; exclusive licensee American Association for the Advancement of Science; Ref. [24], © Wiley Periodicals, Inc. 2019; Ref. [25], © Wiley-VCH GmbH 2021.

coiling [32]. In systems with asymmetric light penetration or spatially heterogeneous photochemistry (e.g., one-sided ultraviolet (UV) crosslinking or gradient photopolymerization), the mismatch can be encoded across the cross-section, producing coupled bending and twisting moments that favor helical rather than planar deformation [33]. Such photo-programmed helices are attractive for remote, spatially resolved actuation and for constructing reconfigurable chiral morphologies.

2.2 Interfacial compression-induced helical formation

Distinct from intrinsic mismatch mechanisms that rely on internal strain gradients, interfacial compression induced helicity arises from external instability of a slender jet under axial compressive stress (Fig. 2(e)). Analogous to Euler buckling of a solid column, a viscous jet undergoes a symmetry-breaking transition from a straight trajectory to coherent helical coiling once the compressive force exceeds its effective bending stiffness. In microfluidic and spinning systems, compressive stress typically originates from resistance

imposed by a downstream boundary (e.g., a collection plate) [34] or viscous drag from a surrounding fluid medium [35]. Depending on rheological distributions and flow conditions, this phenomenon manifests in two regimes: the classic liquid rope coiling (LRC) effect [36] and the hetero-generated rope-coil (HRC) effect [37].

LRC effect. LRC commonly occurs when a highly viscous inner jet penetrates a stagnant or slower-moving outer fluid [22, 38, 39]. The fast inner jet experiences viscous drag from the surrounding medium, effectively decelerating the jet tip and generating axial compressive stress that propagates upstream. When the inner flow dominates, continuous injection overwhelms environmental dissipation, and the jet buckles and deposits into a helical coil [40]. This mechanism is widely observed in everyday viscous flows and serves as the standard paradigm for hydrodynamic coiling.

HRC effect. HRC effect was proposed to explain helix formation under inverse rheological conditions (e.g., a low-viscosity core with a viscous sheath) or systems involving rapid interfacial reactions [37]. In such scenarios, the bulk core lacks sufficient viscosity to

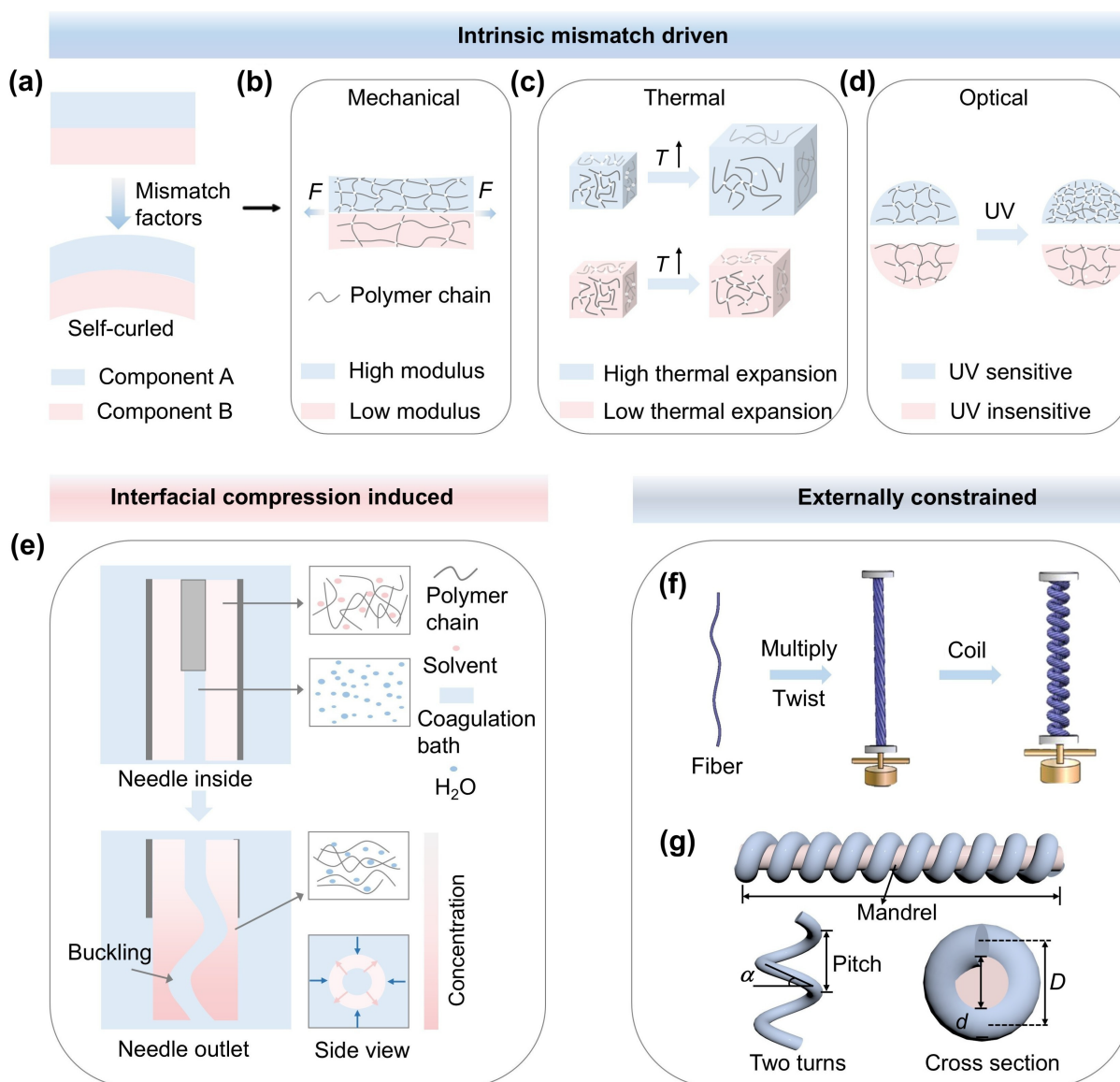


Figure 2 The fabrication mechanisms of helical structure. (a) Strain-induced curvature in the bilayer, (b) mechanical mismatch driven helical formation, (c) thermal expansion mismatch induced helical formation, and (d) UV response mismatch induced helical formation. (e) Interfacial compression induced helical formation. (f) Winding for helical formation. Reproduced with permission from Ref. [30], © Wiley-VCH GmbH 2024. (g) Twisting for helical formation.

sustain buckling. Instead, the effective “buckling rope” is a rapidly formed semi-solid intermediate layer generated by interfacial crosslinking or phase separation [41, 42]. Helical instability is intensified by increasing the outer-to-inner flow-rate ratio, because the high-velocity sheath enhances shear drag and confinement on the nascent intermediate layer. This external forcing compresses the semi-solid shell against the slower-moving or confined core, triggering buckling of the interface itself. HRC mechanisms are particularly effective for constructing embedded helical microchannels and strain-insensitive conductive fibers, expanding helical manufacturing beyond simple viscous-jet coiling.

2.3 Externally constrained helical formation

Externally constrained mechanisms impose geometric or mechanical constraints to force a material into a helical configuration. Two representative routes are twisting and mandrel winding.

2.3.1 Twisting

In solid fibers, torsional buckling emerges through accumulation of shear stress, typically induced by over-twisting (Fig. 2(f)) [30]. Once the torsional energy exceeds a stability threshold, the fiber undergoes a spontaneous transition from a straight cylinder to a helical coil to minimize total elastic energy, effectively converting torsional energy into bending energy [43, 44]. Further twist insertion into an already coiled elastomeric fiber can trigger a secondary instability, transforming simple coils into hierarchical supercoils. This process is governed by the interplay among torsional stiffness, applied tension, and geometric constraints [45].

2.3.2 Mandrel winding

Mandrel winding provides a direct bottom-up route to program coil diameter and pitch using rigid cylindrical mandrels, largely independent of the intrinsic stiffness of the fiber (Fig. 2(g)). Consolidation strategies depend on material chemistry. For

example, programmable filament winding coupled with in situ interfacial click reactions enables seamless, chemically bonded tubular actuators from liquid crystal elastomer precursors [46]. Alternatively, hydrogel-infused yarns can be wrapped around metal shafts and then dried to harden the gel matrix, physically locking a tendril-mimetic architecture without additional chemical crosslinking [47].

3 Fabrication technologies of helical structure

Prevailing helical fabrication technologies include spinning-induced self-coiling such as microfluidic and wet spinning, as well as twisting-enabled coiling and supercoiling, and winding-assisted assembly (e.g., thermal drawing and template manipulation). Collectively, these methodologies enable the fabrication of helical materials spanning various dimensions, progressing from individual 1D fibers to complex, integrated 2D and 3D assemblies (Table 1).

3.1 One-dimensional fiber

Microfluidic spinning provides a precise platform for manipulating multiphase flows at the microscale. By leveraging laminar flow in microchannels, this technique enables continuous production of helical microfibers with well-controlled diameters, typically in the range of 10–500 μm [37, 48]. In many systems, helix formation follows the LRC instability discussed earlier: a viscous inner jet is surrounded by a lower-viscosity sheath flow, and the unbalanced fluidic friction together with axial compressive stress imposed by the outer fluid triggers buckling and subsequent helical coiling. Importantly, key geometric descriptors such as fiber diameter and pitch can be tuned by adjusting capillary orifice sizes and flow-rate ratios [49, 50]. For instance, by engineering injection capillaries, Yu et al. [22, 51] fabricated multicompartamental helical fibers, including Janus and triplex architectures (Fig. 3(a)), enabling chemically heterogeneous helices. Beyond continuous fibers, discrete helical micro-segments can also be generated via downstream manipulation or discontinuous injection [22, 38, 52].

Wet spinning relies on related fluid instabilities to fabricate helical architectures at larger length scales [53, 54]. Under LRC type conditions, an extruded jet experiences axial compressive stress as it impinges on the coagulation bath floor or encounters fluid resistance (Figs. 3(b) and 3(c)), resulting in spontaneous coiling [41]. By tuning parameters such as falling height, nozzle to bath

distance, and collection conditions, researchers have produced helical hollow fibers and elastic coils using wet-spinning routes [55].

Beyond spontaneous coiling during spinning, helical structures can be constructed through post-spinning mechanical shaping. Template-assisted winding is a representative approach in which external geometric constraints are applied to partially cured or compliant fibers to lock in a helical configuration [14, 15, 17, 46]. Zhao et al. [56] wrapped an uncured-core alginate/Clear flex core-shell hydrogel fiber around a rod, reshaping the liquid core into a helix; subsequent curing and shell removal yielded a stretchable helical fiber (Fig. 3(d)).

Mechanical twisting provides another versatile pathway to generate helices. One mode involves plying multiple strands, where two or more fibers are twisted around a common axis to form stable double- or multi-helical structures. The helical morphology is maintained through inter-fiber friction and geometric interlocking, enabling functional helical fibers for sensing and electronics [58, 60, 61]. A second mode exploits over-twisting to induce self-coiling within a single fiber or yarn. In this scenario, accumulated torsional stress eventually exceeds the stability threshold of the filament, leading to spontaneous buckling and self-wrapping to minimize strain energy, thereby forming tight helical coils [43–45, 62, 63]. As illustrated in Fig. 3(e), a yarn is over-twisted to drive a topological transition from a straight filament to a fully coiled helix; the coil is then folded and released to form a torque-balanced self-plied yarn, which can be cut at the folding point to isolate two independent helical electrodes [25]. While twisting routes support continuous processing, the resulting helix size is often constrained to micro- to sub-millimeter scales by the filament diameter and the precision of mechanical control.

To enable programmable internal architectures beyond the limits of conventional extrusion, digital manufacturing routes have also been explored [64–68]. Larson et al. [59] developed a rotational multi-material 3D printing (RM-3DP) platform that achieves sub-voxel control by synchronizing nozzle angular velocity with translational speed. This kinematic coordination enables programmable deposition with tailored helical angles and orientations within a single filament, producing azimuthally heterogeneous architectures (Fig. 3(f)) that can be translated into devices such as helical dielectric elastomer actuators with tunable electromechanical response. In parallel, shear-induced coiling during extrusion offers an alternative route to millimeter-to-centimeter-scale helices without complex nozzle kinematics [69],

Table 1 Comparison of different helical fiber fabrication methods

Methods	Formation mechanism	Materials	Advantages	Limitations	Refs.
Wet spinning	LRC effect, HRC effect, strain mismatch	PEDOT:PSS, PU, (PANa-SWCNT) hydrogels	Scalability, helical channel structure, material versatility	Only 1D fiber, restricted to macroscale	[41, 54, 104]
Microfluidic spinning	LRC effect, HRC effect	Ca-alginate	Precise geometric tunability	Low throughput	[22, 37]
Printing	Strain mismatch, LRC effect	GO/SA, metal	Fully programmable geometry	Restricted to macroscale, low throughput	[69]
Electrospinning	Strain mismatch, GHT-induced curl, Multiple-stage whipping	Ceramic aerogels, PVB, PVDF	Scalability, 3D fibers assembly	Stochastic geometric distribution	[91–92]
Meltblown	Strain mismatch	PP/TPU	Scalability, 3D fibers assembly, high throughput	Stochastic geometric distribution	[57]
Winding	External constraints via physical templates	MXene/Nylon	Material-independent shaping, high structural uniformity	Only 1D fiber restricted to macroscale	[14]
Twisting	Multi-ply twist, overtwist	TPU, PVA/GO	Enhanced structural elasticity	Only 1D fiber, requirement for torque balancing	[44, 58]

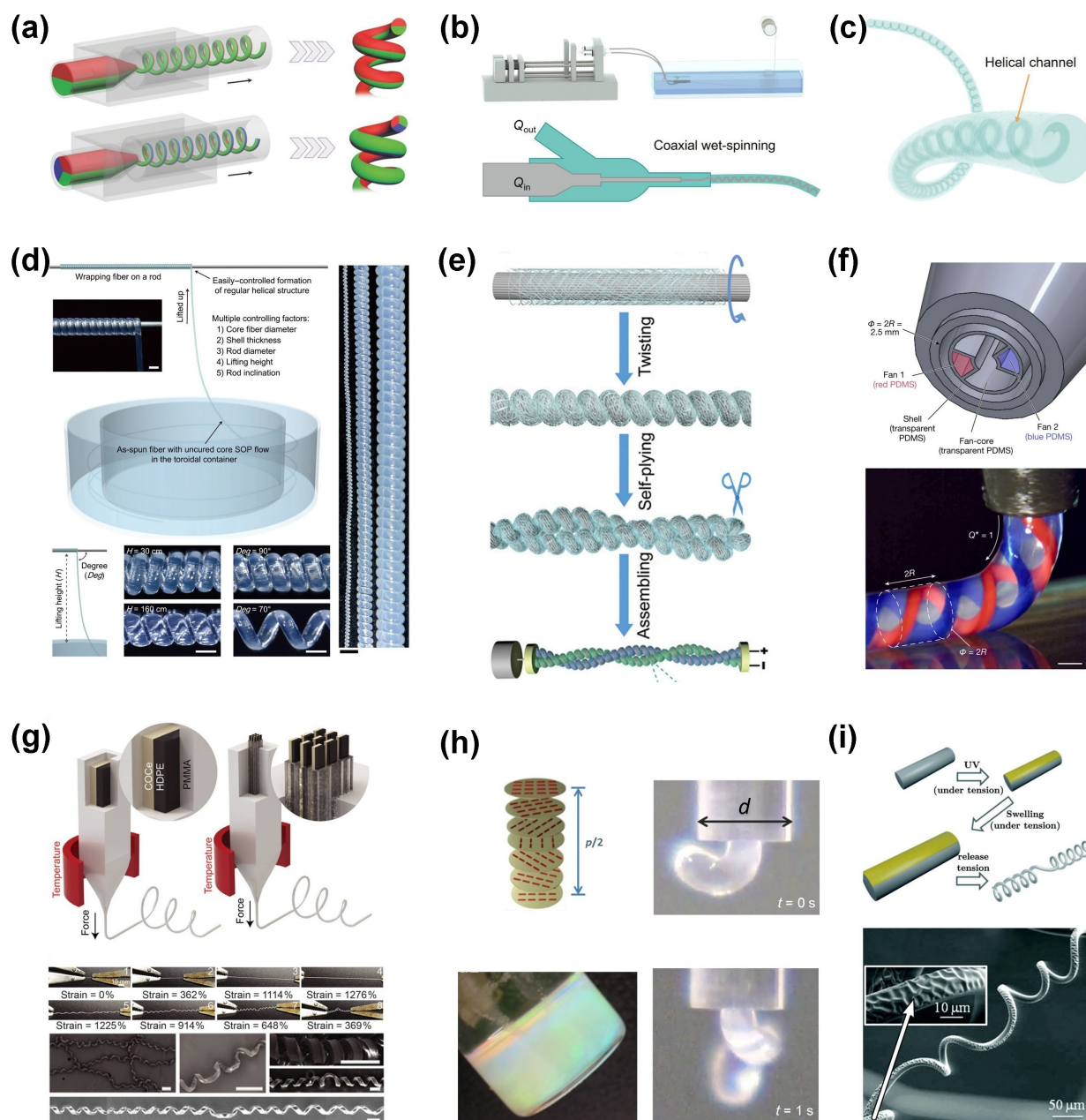


Figure 3 (a) Generation of the multicompartmental helical microfibers by microfluidics. Reproduced with permission from Ref. [22], © WILEY-VCH Verlag GmbH & Co. KGaA 2017. Weinheim Schematic illustration of (b) the co-axial wet spinning system and (c) the obtained helical hollow structure. Reproduced with permission from Ref. [41], © Luo, M. Y. et al. 2025. Advanced Science published by Wiley-VCH GmbH. (d) Helical fiber formation via the winding-based reshaping strategy. Scale bars, 1 (white) and 5 mm (black). Reproduced with permission from Ref. [56], © Zhao, G. X. et al. 2023, some rights reserved; exclusive licensee American Association for the Advancement of Science. (e) Schematic illustration of the preparation of the solid-state electrochemical yarn muscle that integrates two yarn electrodes twisted together and separated by ionic-liquid-infiltrated PVDF-HFP nanofiber separators. Reproduced with permission from Ref. [25], © Wiley-VCH GmbH 2021. (f) 3D model of four-material shell-fan-core nozzle tip and the photograph of four-material PDMS filament deposition. Scale bar, 1 mm. Reproduced with permission from Ref. [59], © Larson, N. M. et al. 2023, under exclusive licence to Springer Nature Limited. (g) The bimorph spring actuators produced via two-step thermal drawing and cold drawing process. scale bars, 200 μm . Reproduced with permission from Ref. [23], © Kanik, M. et al. 2019, some rights reserved; exclusive licensee American Association for the Advancement of Science. (h) Cholesteric liquid crystalline phases in cellulosic solutions. Reproduced with permission from Ref. [75], © Canejo, J. P. et al. 2013; licensee MDPI, Basel, Switzerland. (i) Schematics of curling and wrinkling process of the electrospun fibers and the resultant asymmetrically wrinkled helical fiber. Reproduced with permission from Ref. [76], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2013.

where shear-aligned micro/nano building blocks encode morphogenetic potential directly into printed filaments. Related strategies have further combined 3D printing with thermal processing to stack liquid crystal elastomer (LCE) layers of different orientations; mismatch strain generated during thermal treatment drives the formation of temperature-adaptive helical LCE fibers [70].

Thermal drawing provides a distinctive top-down strategy for producing multifunctional 1D fibers by heating and scaling down a macroscopic preform, enabling the integration of conductors, semiconductors, and insulators within a single cross-section [71]. Although thermal drawing typically yields straight fibers, helical architectures can be engineered through intrinsic mismatch

generated during drawdown [72]. Kanik et al. [23] demonstrated this by co-drawing two polymers with disparate thermal expansion coefficients and crystallization kinetics. After cold drawing, releasing the fiber activates internal stress differentials generated by elastic recoil and crystallization-induced shrinkage, driving spontaneous bending into uniform helical coils (Fig. 3(g)). More commonly, helices can also be produced from as-drawn straight fibers by applying external torque [71, 73] or geometric constraints [74].

Electrospinning-based routes can generate helices through liquid-crystalline ordering or asymmetric self-shaping. Helices have been produced from liquid-crystalline solutions [75, 76], where intrinsic curvature arises from asymmetric contraction associated with an off-center internal disclination line (Fig. 3(h)), leading to differential shrinkage along the fiber axis. More generally, structural asymmetry can be engineered through core-sheath architectures with different deswelling rates [77] or by imposing crosslinking-density gradients across off-axis oriented strips [78], generating competing bending and twisting moments that drive tendril-like coils or even dynamic chiral reversals.

Helical deformation can also be induced via UV-assisted crosslinking strategies. Trindade et al. [33] demonstrated solvent-driven self-shaping in electrospun microfibers comprising a soft core and a stiff, UV-crosslinked outer half-shell (Fig. 3(i)). Upon solvent deswelling, the asymmetric natural lengths of the core and shell generate internal bending moments that drive spontaneous helical curling; at sufficiently high curvature, secondary surface-wrinkling instabilities can also emerge, offering additional hierarchical features.

3.2 Two-dimensional and three-dimensional fiber assemblies

While the methods above demonstrate controllable helix formation at the single-fiber level, practical deployment is often constrained by scalability and macroscopic integrity. Individual helical fibers are difficult to process into large-area constructs and to maintain stable, interconnected pore architectures required in real devices. Assembling helical fibers into 2D membranes and 3D porous assemblies addresses these limitations by combining the spring-like mechanics of helical building blocks with high porosity, enlarged accessible surface area, and robust structural cohesion.

3.2.1 2D helical fibrous membranes

A representative route to 2D helical membranes relies on electrospinning-based jet programming, where controlled asymmetry in the jet or cross-section induces stress mismatch during rapid solvent evaporation and solidification [11, 79–83]. In a series of studies, off-centered core-shell spinnerets were designed to generate eccentric or side-by-side configurations by creating asymmetric electric fields and polymer flow [12, 84–87] (Fig. 4(a)). The resulting helical morphology in nonwovens is attributed to intrinsic stress mismatch between the two components, whose differential mechanical responses are frozen into the fiber during rapid solidification. Building on this framework, tri-fluid electrospinning was further used to increase structural complexity, enabling multilevel fibers with helical grooves or hollow features [3, 4, 9]. High-speed imaging captured the dynamic whipping instability and the distinct bending behavior of compound jets (Fig. 4(b)), while SEM confirmed uniform and continuous helical fibers in the collected membranes (Fig. 4(c)), demonstrating the

capability of multi-fluid electrospinning to encode complex helical morphologies at the nonwoven level. Beyond electrospinning, the strain mismatch induced coiling concept has also been extended to melt blown, offering substantially higher throughput. By incorporating a specialized swirl die into the melt-blowing setup [24, 57, 88, 89] (Figs. 4(d) and 4(e)), nonwoven fabric composed of entangled helical microfibers were produced from polymer blends. This translation from electrospinning to melt blowing highlights a practical pathway toward scalable manufacturing of helical fiber mats.

3.2.2 3D fluffy assemblies and bulk architectures

Moving from planar membranes to bulk 3D constructs, recent advances have leveraged airflow-driven jet manipulation and multi-jet deposition to directly generate impact-induced buckling fibers and lock them into self-entangled networks [90]. Cheng et al. [91] reported a grid-induced homogeneous turbulence spinning (GHTS) strategy that converts high-speed airflow into homogeneous turbulence using multi-hole porous grids (Fig. 4(f)). The resulting multiscale and isotropic eddies continuously stretch, bend, and fold polymer jets, which are rapidly frozen into highly curved morphologies by solvent evaporation. This needless approach achieves approximately an order-of-magnitude higher productivity than conventional solution blow spinning and enables scalable fabrication of 3D highly curved nanofiber assemblies. Similarly, Yang et al. [92] employed multiple-jet electrospinning to construct superelastic sponges. By tuning solution conductivity and solvent volatility, enhanced whipping instability and rapid phase separation allow curling to compete effectively with electrostatic straightening, so that the jets are fixed into helical shapes prior to full stretching. Curly fibers then interlock upon deposition to form a cohesive, self-entangled 3D network (Fig. 4(g)). This design translates microscopic coil elasticity into macroscopic bulk superelasticity, yielding robust and washable porous materials with improved durability compared with linear-fiber assemblies.

For brittle inorganic systems, in situ buckling and assembly strategies offer an effective route to transform intrinsic brittleness into structural compliance at the aerogel level. Dang et al. [93] developed an off-axis electrospinning strategy to fabricate highly buckled ceramic nanofibrous aerogels. Using dual precursors with different elastic moduli and volatilization rates, an off-axis jet trajectory introduces asymmetric deformation during solidification, driving spontaneous curling and entanglement into a tortuous 3D network during deposition (Fig. 4(h)). This in situ buckling and assembly process yields ceramic aerogels with ultra-large stretchability and tensile-insensitive thermal insulation, demonstrating a scalable pathway to build functional 3D metamaterials without complex post-processing. Pushing material-process boundaries further, Dong et al. [94] used coaxial electrospinning to transform intrinsically nonspinnable, polymer-free ceramic sols into continuous helical microsponges. By encapsulating a low-viscosity sol within a polymer shell, mismatch in solidification kinetics generates internal stress that triggers spontaneous buckling into helical architectures. The approach enables highly dense ceramic microstructures (e.g., TiO_2 and ZrO_2) with unusual flexibility and toughness compared with conventional porous ceramics derived from binders. Beyond solution-based routes, chemical vapor deposition (CVD) provides a robust pathway to engineer crystalline helical carbon architectures. Li et al. [16] demonstrated controlled synthesis of spring-like helical carbon nanofibers via catalytic CVD, where growth kinetics were regulated

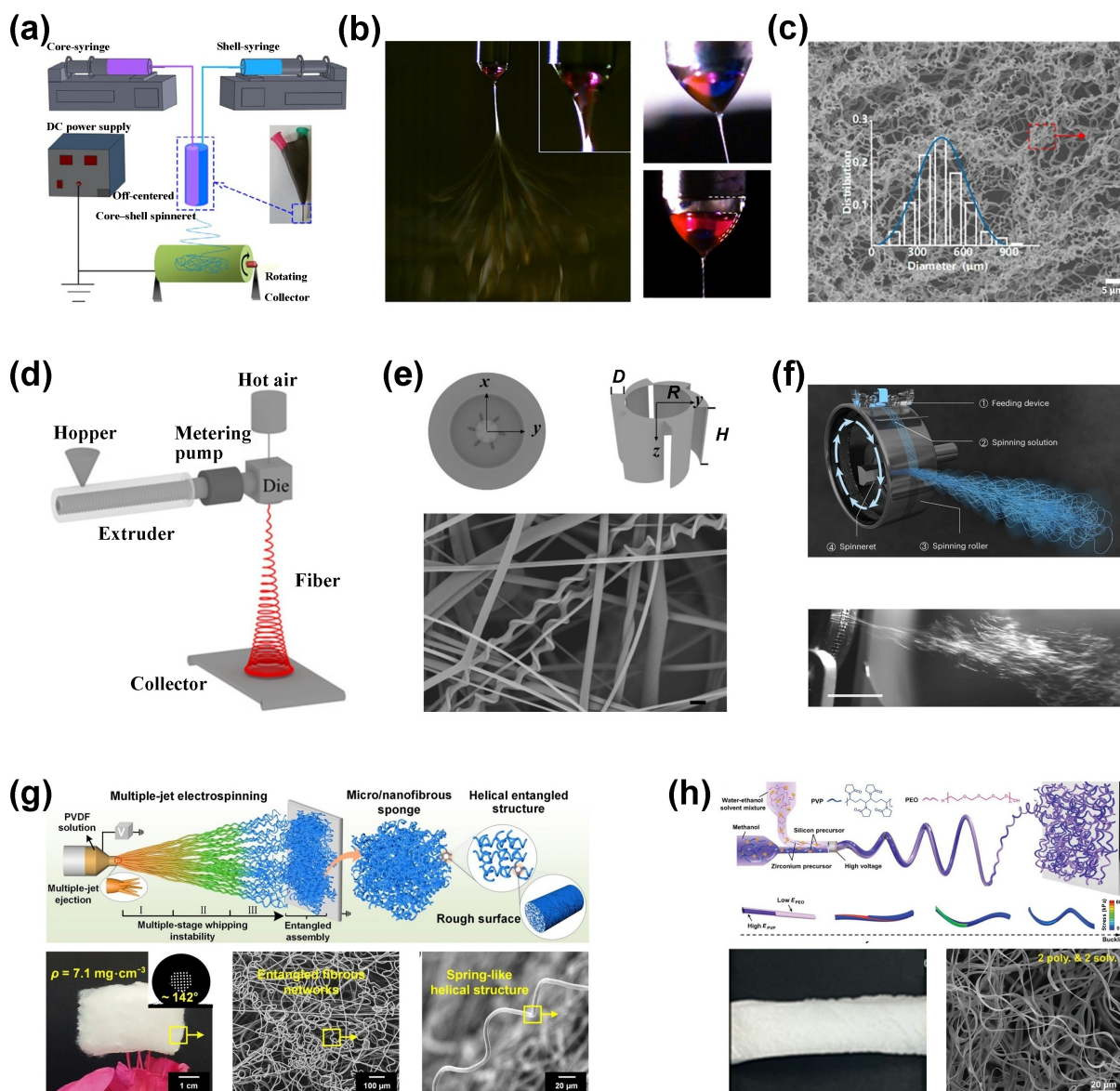


Figure 4 (a) Schematic of off-centered co-electrospinning system. Reproduced with permission from Ref. [84], © American Chemical Society 2015. (b) High-speed photographs of the tri-fluid electrospinning process and (c) SEM image of the helical fiber assembly and its diameter distribution. Reproduced with permission Ref. [4], © Zhao, T. N. et al. 2021. Published by Elsevier Ltd. (d) Schematic of the melt-blowing device. Reproduced with permission from Ref. [57], © Wiley Periodicals, Inc. 2019. (e) Schematic of the swirl die with the auxiliary device, and SEM image of the melt-blown helical fibers. scale bar, 10 μm . Reproduced with permission from Ref. [24] © Wiley Periodicals, Inc. 2018. (f) Schematic representation of the GHTS device and high-speed video image demonstrating HCNFs fabricated via the GHTS system. Scale bar, 20 mm. Reproduced with permission Ref. [91], © Springer Nature 2025. (g) Fabrication and structural characterization of the MNFS Reproduced with permission from Ref. [92], © Yang, F. J. et al. 2025. (h) Fabrication and characterization of the highly-buckled fibrous aerogel. Reproduced with permission from Ref. [93], © Wiley-VCH GmbH 2024.

to induce spiral morphology.

4 Applications

4.1 Sensing

4.1.1 Strain sensors

Helical architectures offer distinct advantages for strain sensing, as external deformation is primarily accommodated through geometric uncoiling rather than intrinsic material stretching. As a result, even small applied strains can induce pronounced structural reconfiguration, leading to amplified electrical or ionic signal

variations [95–99]. This geometry-dominated deformation mechanism enables high sensitivity at low strain levels, broad sensing ranges, and improved cyclic stability compared to conventional straight fiber-based strain sensors (Table 2).

Single helical fiber-based strain sensors. Single helical architectures represent one of the most extensively investigated categories in this field, particularly in resistive sensing configurations [100–103]. Chen et al. [104] developed a single-helical conductive fiber by doping the conductive polymer PEDOT:PSS into a thermoplastic polyurethane (TPU) matrix and subsequently spinning the composite solution. Owing to the winding rope effect of the PEDOT:PSS/PU system, spontaneous formation of a helical

Table 2 Sensing performance comparison of helical fiber-based sensors

Sensing type	Materials	Sensitivity	Key parameter	Refs.
Resistance	PU/PEDOT:PSS fiber	Gauge factor: 0.56	High elongation at break (up to 950%), exceptional elasticity (400%)	[100]
Resistance	PU/Ag wires yarn	Gauge factor: 2.6–9.3, response time: 120 ms	Strain range: 0%–150%, good cycling performance (1200 cycles)	[108]
Resistance	Latex/LM yarn	Good sensitivity (0.82 for tension, 12.6 N ⁻¹ for pressure), rapid response time (10 ms)	Exceptional softness (0.23N at 100% strain), wide strain range (10%–100%), high durability (over 100,000 cycles)	[109]
Resistance	Alginate/agar/carbon nanotube fiber	Gauge factor: 1.79, response time: 0.5 s	Adhesive, rate-agnostic stability	[107]
Capacitive	Silicone tube/LM yarn	Gauge factor: 1.07	Working range: 0%–100%, high durability (6000 cycles), fast temperature response	[113]
Capacitive	TPU/IL/Ag yarns	Gauge factor: 6.46, response time of 134 ms	Superb durability over 3300 cycles, 0%–140% strain range, moisture resistance	[19]
Magnetic	TPU/Cu fiber	Gauge factor: 0.197, strain range of 0%–100%	Long-term stability (100,000 cycles), wide working temperature range (–30 to 160 °C)	[114]
Magnetic	Elastomeric resin/LM fiber	Detection limit: 50 mN, working range: 0–250 Pa	high durability (1000 cycles in 100% strain), electrical stability (400% strain)	[98]
Magnetic	Ecoflex-NedFeb/rubber fiber	Gauge factor: 0.054 kPa ⁻¹ , working range: 0%–2485%	Stable electrical output over 2000 cycles, operable underwater	[31]
Triboelectric	CNTs/PU yarn	Open-circuit voltage: 2 V, short-circuit current: 20 nA	Output stability over 1000 cycles, working range: 0%–100%	[111]

structure was achieved (Fig. 5(a)). The resulting helical fiber simultaneously exhibited high electrical conductivity (650 S·cm⁻¹) and exceptional stretchability (up to 950%). Benefiting from resistance variation of the conductive network under tensile deformation, the PEDOT:PSS/PU helical fiber sensor demonstrated stable strain response with a gauge factor (GF) of 0.56 and excellent cyclic durability. Similarly, Yu et al. [105, 106] fabricated a coaxial helical fiber strain sensor using a microfluidic spinning technique, where poly (vinylidene fluoride) (PVDF) served as the shell layer and an ionic liquid as the core. The helical coaxial architecture enabled sensitive strain detection while maintaining excellent wearability. The sensor was capable of monitoring joint motion angles within a strain range of up to 70%, highlighting its suitability for wearable motion tracking. To further improve skin conformability and mechanical compliance, Xing et al. [107] reported an ionic conductive gel fiber composed of alginate, agar, and carbon nanotubes. After a post-twisting treatment, the gel fiber adopted a helical morphology and functioned as a highly stretchable strain sensor. The resulting device exhibited fast response time (< 0.5 s), a maximum strain of 130%, and excellent skin adhesion, enabling 360° spatiotemporal perception of human motion.

In addition to self-assembled helical fibers, winding conductive yarns around elastic substrates provides another effective strategy for constructing helical strain sensors. Tong et al. [108] wrapped silver-plated nylon yarns around polyurethane (PU) filaments to fabricate a highly stretchable helical strain sensor (Fig. 5(b)). The synergistic interaction between the elastic PU core and the outer helical Ag yarn enhanced the mechanical robustness and stretchability, while the conductive Ag yarn ensured high electrical conductivity. Experimental results showed that with a pitch of 1.25 mm, the sensor achieved a strain range of up to 150% and a gauge factor of 2.6. When integrated into a glove, the helical fiber sensor enabled real-time monitoring for hand function rehabilitation training. To further extend the working strain range, Ding et al. [109] constructed helical latex yarns and subsequently loaded liquid metal onto the elastic helical substrate to form a

highly deformable strain sensor (Fig. 5(c)). The resulting latex/liquid metal helical sensor exhibited extraordinary linearity within a strain range of 10%–100%, with a goodness-of-fit value exceeding 0.997. Additionally, the sensor demonstrated rapid response (< 10 ms), high strain resolution (down to 0.3%), and remarkable durability over more than 100,000 stretching cycles, underscoring the effectiveness of helical geometry in stabilizing electrical performance under large deformation.

Beyond resistive sensing, triboelectric helical fiber-based strain sensors have also attracted significant attention. Zhou et al. [110] fabricated a triboelectric helical fiber by winding conductive polyethylene terephthalate (PET) yarns around elastic rubber fibers and encapsulating the structure with polydimethylsiloxane (PDMS). Owing to the difference in electron affinity between the PDMS and PET layers, dynamic voltage signals were generated during tensile deformation. The sensor exhibited fast response, high voltage output within a strain range of 100%, and stable electrical performance over 6000 stretching cycles. Based on this helical triboelectric strain sensor, a sign-language translation system was developed for human-machine interaction and communication. Gao et al. [111] further demonstrated a triboelectric helical fiber with a zebra-patterned architecture by combining electrospun PU nanofibers and electro-sprayed carbon nanotubes (CNTs) to form a Janus PU/CNT membrane, followed by a twisting process. The resulting helical fiber exhibited alternating PU and CNT domains along the fiber axis. Due to differences in electron affinity, numerous microscopic CNT/PU interfaces generated a self-frictional triboelectric effect. Under tensile strain, the zebra-patterned helical fiber produced stable and repeatable voltage signals, demonstrating the potential of structurally engineered helical fibers for triboelectric strain sensing.

Double-helical fiber-based strain sensors. Double-helical architectures provide an effective platform for strain sensing because the intertwined geometry naturally accommodates paired functional components (e.g., two electrodes or two coils) and enables strain-induced modulation of their relative spacing, overlap, or coupling strength [112]. Capacitive sensing is one of the most

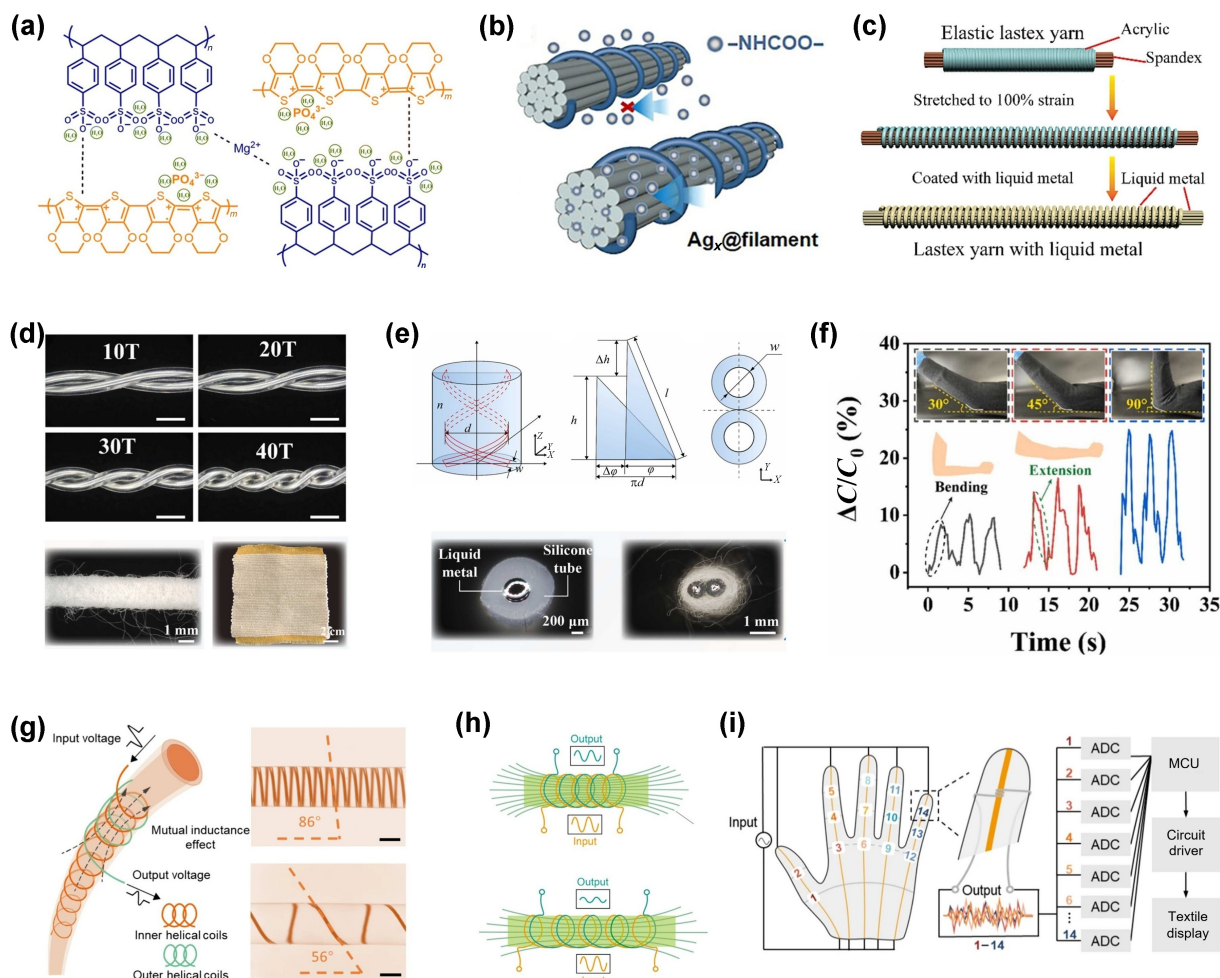


Figure 5 (a) Diagram of compound interactions. Reproduced with permission from Ref. [104], © The Royal Society of Chemistry 2023. (b) Schematic diagram of interface interaction between WPU and helical structured fiber. Reproduced with permission from Ref. [108], © American Chemical Society 2025. (c) Schematic illustration for fabrication process of LM sensing fiber. Reproduced with permission from Ref. [109], © Elsevier B.V. 2023. (d) Optical images of double helix core yarns with different twists, (e) the double helix morphology of the liquid metal in the yarn, the expanded view of the double helix structure of the yarn, and the cross-sectional views of the yarn, and (f) relative change in capacitance of the sensor according to bending motions of elbow. Reproduced with permission from Ref. [113], © Elsevier Ltd. 2022. (g) Schematic diagram showing the coaxial coiling structure of a fiber strain sensor, (h) schematic diagram showing the working principle of the fiber strain sensor, and (i) Schematic diagram of the circuit of the electronic glove and schematic diagram of cooperative work between electronic gloves and the textile display. Reproduced with permission from Ref. [114], © Donghua University, Shanghai, China 2024.

representative strategies enabled by double-helical fiber structures. Fu et al. [113] fabricated a liquid-metal (LM)-based double-helical core-sheath yarn by twisting two thin silicone tubes injected with LM and subsequently wrapping the assembly with skin-friendly yarns (Fig. 5(d)). In this design, the LM cores function as electrodes, while the silicone tube wall serves as the dielectric layer. Upon stretching, the thickness of the silicone wall changes, resulting in a measurable capacitance variation (Fig. 5(e)). The resulting sensor exhibited a workable strain range of 100%, high sensitivity ($GF = 1.07$), ultralow hysteresis, and good durability over 6000 cycles. Owing to its reliable capacitive response, the device was further applied to quantify human joint motion with different bending amplitudes (Fig. 5(f)). In a related approach, Feng et al. [19] constructed a double-helical capacitive strain sensor by alternately winding two conductive silver yarn layers onto a PU filament and encapsulating the structure using an ion gel as the dielectric medium. Benefiting from the strain-modulated electrode geometry and stable dielectric encapsulation, the sensor delivered a high sensitivity ($GF = 6.46$) at 140% strain and maintained stable output over 3000 stretching cycles. Notably, the ion-gel-based

encapsulation also imparted water and sweat resistant performance, facilitating seamless integration into garments for practical wearable applications.

Beyond capacitive transduction, double-helical fiber architectures can also enable electromagnetic induction-based strain sensing by configuring two electrically isolated helical coils with tunable mutual coupling. Ai et al. [114] reported a PU based double-helical fiber sensor by winding two electrically insulated copper coils onto a PU fiber and encapsulating the assembly (Fig. 5(g)). When a voltage signal is applied to the inner coil, an induced voltage is generated in the outer coil via mutual inductance; stretching the fiber alters the coil geometry and coupling strength, thereby modulating the induced signal (Fig. 5(h)). The sensor exhibited excellent linearity ($R^2 \approx 0.99$) over a strain range of 100% and maintained stable operation across a wide temperature window (-30 to 160 °C). When integrated into a glove, it enabled accurate hand-motion sensing under diverse environmental conditions (Fig. 5(i)). Qin et al. [31] further developed an inductive helical fiber sensor with a hierarchical helical configuration. In their design, a copper helical coil was encapsulated with an Ecoflex elastomer

containing $\text{Nd}_2\text{Fe}_{14}\text{B}$ particles, and a pre-stretched rubber elastomer was introduced to generate a higher-order helical architecture. After magnetization, tensile deformation of the internal copper coil produced an induced electromotive force by cutting magnetic flux lines from the surrounding magnetic elastomer. The device generated a maximum output of 90 μV at 2845% strain and maintained stable performance over 2000 cycles, highlighting the potential of helical inductive mechanisms for ultra-large deformation strain sensing.

4.1.2 Implantable biosensors

Implantable bioelectronic devices are required to operate in complex and dynamic biological environments, where soft tissues undergo continuous deformation with varying amplitudes, frequencies, and mechanical modes [115, 116]. Unlike wearable systems, implantable sensors must maintain long-term mechanical compliance, stable signal transduction, and minimal mechanical mismatch with surrounding tissues to mitigate inflammation, fibrosis, and signal drift. Conventional linear or planar electronic components often suffer from rigidity-induced stress concentration and limited deformability, rendering them unsuitable for chronic implantation. In this regard, helical fiber architectures provide an effective mechanical interface between electronic devices and living tissues, as their spring-like geometry enables large elastic deformation, mechanical buffering, and enhanced conformability under physiological motion. In current studies, helical fiber based implantable biosensors can be broadly categorized into three representative classes: (i) capacitive double-helical strain sensors for monitoring slow and relatively large tissue deformation (e.g., tendon/ligament repair), (ii) self-powered triboelectric double-helical sensors for cyclic musculoskeletal motion monitoring where continuous external powering is undesirable, and (iii) piezoelectric helical devices for capturing subtle and higher-frequency organ motions such as cardiac beating.

Yang et al. [117] constructed a capacitive double-helical fiber strain sensor and implanted it for monitoring tissue strain during tendon/ligament repair (Fig. 6(a)). In their design, surgical sutures functionalized with PEDOT:PSS were encapsulated with Ecoflex, and two encapsulated sutures were subsequently co-wound into a double-helical configuration followed by further Ecoflex encapsulation. The resulting sensor responded to extremely small strains down to 0.25% and operated stably within a 0%–10% strain window. Notably, it maintained stable signal output over 300,000 stretching cycles. After implantation, the double-helical structure underwent reversible geometric transformation, enabling reliable and repeatable strain monitoring without mechanical failure (Fig. 6(b)). The device acquired real-time, clinical-grade strain data while exhibiting high biocompatibility (Fig. 6(c)), highlighting the suitability of helical architectures for long-term musculoskeletal monitoring.

While capacitive helical sensors are well suited for slow tissue deformation, many physiological processes involve cyclic and repetitive motions for which continuous external power supply is impractical or undesirable. Sheng et al. [118] designed a self-powered double-helical sensor for ligament strain monitoring by winding an ionically conductive organic gel fiber with a silicone elastomer fiber (Fig. 6(d)). Owing to the high electron affinity of silicone, contact-separation between the silicone fiber and the gel electrode during deformation generated an induced electrical potential (Fig. 6(e)). The sensor exhibited outstanding flexibility and

stretchability (> 600%) and preserved stable electrical output over a period of six months. When implanted into the patellar ligament of a rabbit knee, it enabled real-time monitoring of ligament stretch and associated muscle stress (Fig. 6(f)), demonstrating the promise of triboelectric helical fibers for chronic, battery-free implantation.

Helical fiber-based devices have also been explored for implantable cardiac monitoring, where signals originate from subtle, continuous, and higher-frequency mechanical motions. Zhang et al. [119] developed a piezoelectric hydrogel (PH) based on PVDF-TrFE/cellulose and induced a helical morphology via strain mismatch with an encapsulation layer (Fig. 6(g)). Benefiting from the deformability of the three-dimensional helical architecture, the device when connected to pacemaker leads effectively captured cardiac beating signals, while simultaneously offering self-powered capability, skin-like flexibility, and high mechanical strength (Figs. 6(h) and 6(i)).

Beyond 1D helical fibers, 2D helical fibrous membranes/textiles have also been applied in implantable systems. Liu et al. [120] fabricated biocompatible and mechanically compliant PCL-based helical microfibers using a phase-transition microfluidic spinning technique. After weaving the PCL helical fibers into a stretchable 2D planar textile, the construct was implanted as an artificial skin substitute, preventing incisional hernia formation and promoting wound healing without adhesion.

4.1.3 Strain-insensitive conductors

Stretchable conductive fibers are essential building blocks for wearable and implantable electronics. However, most straight fibers suffer from pronounced resistance variation under tensile deformation due to intrinsic material stretching, microcrack formation, and disruption of conductive networks. Introducing helical geometry provides an effective structural strategy to decouple electrical conduction from external strain, because applied deformation is primarily accommodated through geometric uncoiling rather than elongation of the conductive pathway. As a result, helical conductive fibers can maintain nearly constant electrical resistance over large strain ranges, enabling strain-insensitive electronic performance.

From a fabrication perspective, helical strain-insensitive conductors are commonly realized through three representative routes: pre-stretching induced self-coiling, winding enabled strategies, and twisting enabled methods. Pre-stretching induced self-coiling provides an autonomous route to generate helical conductive fibers by exploiting intrinsic stress mismatch between different material components. Cheng et al. [20] bonded an encapsulated conductive polyethylene (PE) helical yarn onto a pre-stretched silicone elastomer; after strain release, the mismatch in shrinkage triggered spontaneous self-coiling into a helical conductor (Fig. 7(a)). The resulting fiber exhibited a low initial resistance of 0.5 $\Omega\cdot\text{cm}^{-1}$ and reversible deformation up to 2000% strain. Under stretching, the internally formed hierarchical coiled structure acted as a mechanical buffer, preventing direct deformation of the conductive component; consequently, the resistance increased by only $\sim 10\times$ even at 2000% strain, ensuring reliable electrical connection without catastrophic failure (Fig. 7(b)). Yang et al. [121] bonded a copper wire to a pre-stretched PU fiber and obtained a three-dimensional helical conductor upon release (Fig. 7(c)). By tuning the pre-stretching ratio, the final deformability of the helical conductor could be adjusted, reaching a maximum elongation of $\sim 400\%$. The resulting fiber demonstrated excellent

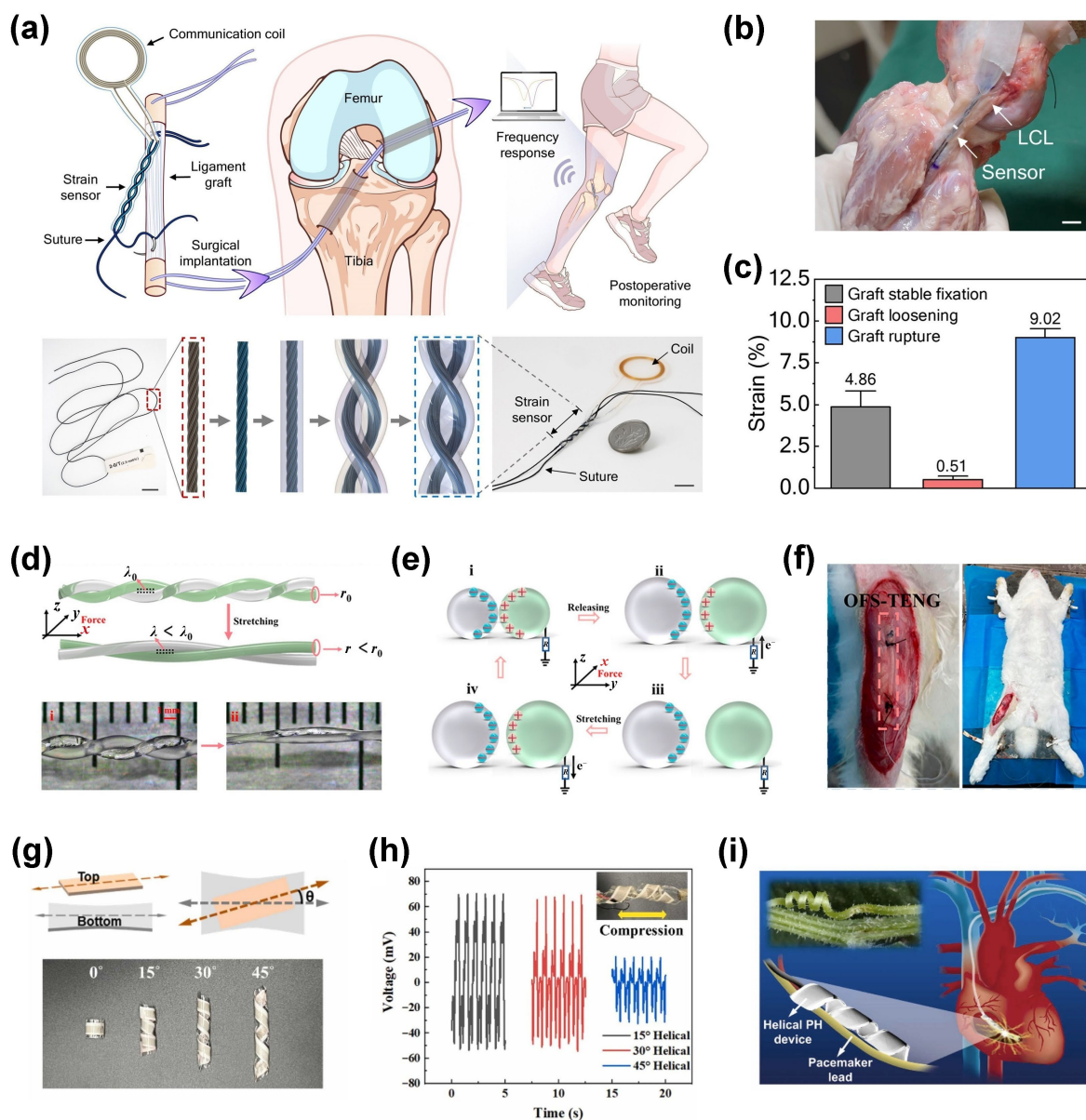


Figure 6 (a) Schematic diagram of the implantation scenario of the strain sensing system and the fabrication process of strain sensor from raw sutures, conductive sutures (functionalized with PEDOT:PSS), composite sutures (encapsulated with medical-grade silicon elastomer), and woven double helix capacitive sensor, (b) photograph of the lateral collateral ligament integrated with the sensor system, and (c) statistics of sensor response under various conditions in the ACLR model ($P < 0.05$, $n = 5$). Gray, graft implanted solidly. Red, graft loosening. Blue, graft rupture. error bars represent the SD. Reproduced with permission from Ref. [117], © Yang, G. M. et al. 2025. Some rights reserved; exclusive licensee American Association for the Advancement of Science. (d) Schematic diagram showing the two states of a double helix structure fiber when stretched, and microscopic images of the two states of the double helix structure fibers under stretching corresponding to the fiber behaviors in panel, (e) Working mechanism of the OFS-TENG in stretching, and (f) photos of the OFS-TENG implanted on the patellar ligament of the rabbit knee. Reproduced with permission from Ref. [118], © American Chemical Society 2022. (g) Method of using the strain effect within a misoriented bilayer to induce self-wrapping, and digital image of the helical PH devices with different geometries obtained by tuning the misorientation angle, (h) voltage outputs generated from the helical PH devices under compression and (i) Schematic of cardiac energy harvesting enabled by integrating the helical PH device with an existing pacemaker lead. Reproduced with permission from Ref. [119], © Zhang, C. et al. 2026, published by Elsevier Ltd.

electromechanical stability, with nearly unchanged resistance at 200% strain (Fig. 7(d)). When integrated with micro-LEDs into textiles as flexible interconnects, the helical conductor maintained stable electrical connections under deformation. Moreover, its waterproof performance enabled reliable operation even when the electronic textile was immersed in water.

Winding-enabled strategies represent a straightforward and intuitive approach to fabricate helical conductive fibers by mechanically winding conductive filaments around elastic cores,

mandrels, or temporary supports, followed by fixation via encapsulation or curing [122–124]. Zhao et al. [125] wound Ag wires around a TPU fiber and encapsulated the assembly with waterborne polyurethane (WPU) to form a primary helical conductor. The conductor was then secondarily wound on a spool and thermally cured to generate a hierarchical helical architecture (Fig. 7(e)). The resulting superelastic conductive fractal helix fiber (FHF) exhibited a diameter of $\sim 3\text{--}5\text{ mm}$ and a high initial conductivity of $\sim 6.3 \times 10^7\text{ S}\cdot\text{m}^{-1}$. Importantly, the two-level helical

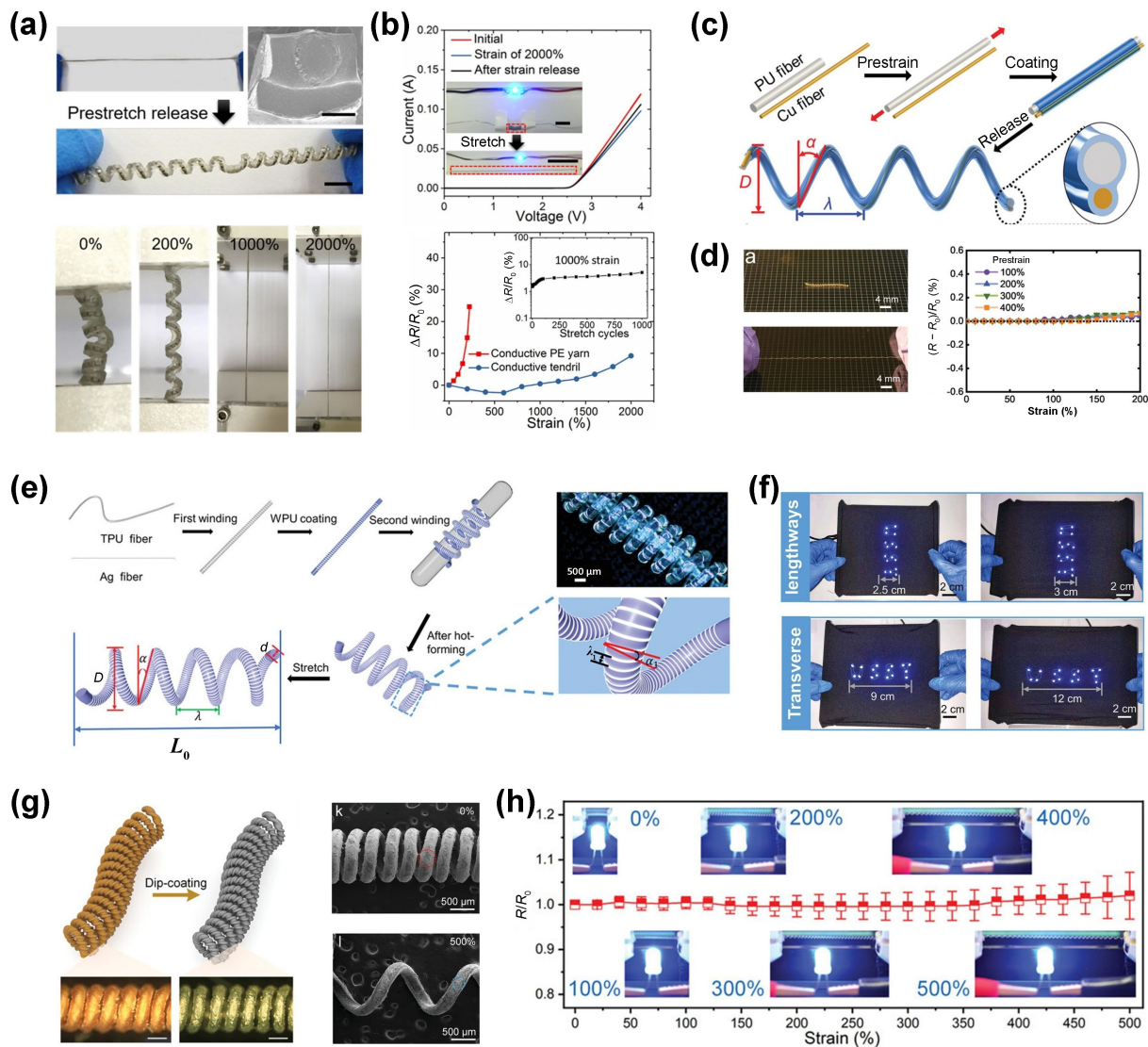


Figure 7 (a) photographs of the conductive tendrils with prestrain of 200% being stretched to strain of 2000% and (b) the current-voltage curves of a LED at initial, stretching (strain of 2000%), and releasing states, and the relative resistance variation of the conductive PE yarn and the conductive tendrils versus the applied stretch strain. Reproduced with permission from Ref. [20], © American Chemical Society 2018. (c) Fabrication process of the 3D helical fiber and (d) a 16 mm long conductive helical fiber in its relaxed state and after being stretched to 65 mm, and resistance change of the 3D helical fibers with 100%, 200%, 300%, and 400% prestrains at different stretching strains. Reproduced with permission [121], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2020. (e) Schematic of the fractal helix fiber (FHF) fabrication, (f) Wearable lighting fabric made from FHF stretched in the length direction and transverse direction with the LEDs turned on. Reproduced with permission [125], © Wiley-VCH 2023. (g) Schematic illustration of the preparation of SHCF and corresponding optical micrographs, and the SEM images of SHCFs at 0% strain and 500% strain, and (h) the variation in normalized resistance of SHCF to tensile strain ranging from 0% to 500%. Reproduced with permission [127], © Wiley-VCH GmbH 2023.

deformation avoided direct strain on the conductive layer, leading to an ultralow relative resistance change ($\Delta R/R_0$) of only 0.166% at an extreme strain of 5600%, and stable resistance over 10,000 stretching cycles. When used as a flexible circuit integrated onto textiles, the FHF enabled stable LED operation without electrical failure even under high strain (Fig. 7(f)). Similarly, Cheng et al. [126] dip-coated cotton fibers with Ag nanowires (AgNWs), wound the coated fibers around a PU core, and encapsulated the structure with PDMS to obtain a helical conductive fiber. The resulting conductor exhibited high conductivity ($4018 \text{ S}\cdot\text{m}^{-1}$) and stretchability (500%). When integrated as a flexible wire in circuits, it maintained stable LED connectivity under 200% strain, demonstrating practical utility for stretchable interconnects.

Twisting-enabled methods generate helical conductive fibers by introducing torsional stress into conductive or composite filaments,

which subsequently relax into coiled or supercoiled geometries. Wu et al. [127] prepared an aramid nanofiber/poly(vinyl alcohol) (ANFs/PVA) fiber via wet spinning, applied clockwise twisting to form a helical morphology, and then impregnated the helical fiber with AgNWs to obtain a conductive ANFs/PVA helical fiber (Fig. 7(g)). Benefiting from a tendrils-inspired homochiral coiled microstructure, the conductor achieved a maximum elongation of 958% while retaining a high tensile strength of 130 MPa. Notably, the electrical resistance remained nearly unchanged within a 0%–500% strain range (Fig. 7(h)), underscoring the effectiveness of twisting-induced helicity in stabilizing conductive pathways under deformation. Lu et al. [128] further demonstrated a LM-based helical conductor by blade-coating intrinsically stretchable LM onto a PU nanofiber membrane and subsequently applying a twisting process to form a helical conductive fiber. Owing to the high

conductivity and fluidity of liquid metal, the resulting PU/LM helical conductor exhibited stable electrical performance and recoverable deformation up to 1500% strain, and maintained stable electrical signals under cyclic stretching, highlighting its promise for highly stretchable and reliable soft electronics.

4.2 Actuation

The unique geometry of helical microstructures enables exceptional morphing capability, making them attractive candidates for artificial muscles and soft robotic systems. A defining feature of helical actuators is their role as geometric amplifiers: Small intrinsic deformations of the constituent materials can be converted into large macroscopic linear strokes or torsional rotations. This geometry-dominated conversion helps overcome the limited strain of many bulk materials and enables programmable responses with high stroke and useful work output. In this section, helical actuators are categorized according to their primary driving stimuli, including thermal, humidity, and electrochemical triggers.

4.2.1 Thermal actuation

Thermal helical actuators generate motion from temperature changes or Joule heating. Although the intrinsic thermal strain of most materials is limited, helical architectures can amplify small expansion into substantial displacement. Two dominant mechanisms are commonly exploited. The first relies on cross-sectional mismatch in thermal expansion between bonded components, which creates an internal bending moment and drives coiling or contraction [129]. For example, Cheng et al. [20] developed biomimetic conductive tendrils by coating pre-strained elastomeric fibers with a rigid conductive sheath. As shown in Figs. 8(a)–8(c), Joule heating activates contraction driven by the restoring force of the elastomeric core against the rigid sheath, enabling reversible muscle-like actuation under load. This architecture exhibits superior passive stretchability (> 2000%) and can lift loads up to 120 times its own weight, with contraction synchronized to the thermal input during power cycling. Using a scalable fiber-drawing route, Kanik et al. [23] achieved similar functional asymmetry through a bi-material preform consisting of an elastomer and a thermoplastic. Cross-sectional images (Fig. 8(d)) highlight the intimate bonding and the role of cold drawing in encoding spontaneous coiling. Upon activation, the stored internal stress drives large shape transformation and enables heavy load lifting, exceeding 650 times the fiber weight. Related bilayer designs have also been extended to laminated thermoplastic films for programmable three-dimensional shape morphing.

The second thermal mechanism is twist-driven actuation, where anisotropic thermal expansion within highly twisted fibers is converted into untwisting and rotation due to geometric constraints [21]. Recent advances have incorporated Ag nanoparticles to enable low-temperature actuation ($\sim 83^\circ\text{C}$) and proprioceptive sensing, allowing the actuator to self-report its actuation state without external sensors. When rotation is restricted, the generated torque can be converted into strong axial contraction. In general, bilayer helices are effective for large strain amplitudes, whereas twist-driven architectures often provide higher output stress and power density. Building on twist-based actuation, Li et al. [130] introduced a spiral hollow fiber (SHF) that integrates actuation within a microfluidic channel. By using internal fluid flow to enhance heat transfer, the SHF achieved an ultrafast response of 0.88 s, approximately 27 times faster than air-driven heating, together with reversible rotation. Structurally, the hollow geometry (Fig. 8(f)) removes the

low bias angle core region present in solid fibers and increases the average bias angle across the wall, improving torque conversion efficiency. This design enabled strong mechanical output (Fig. 8(g)) and was further demonstrated as an intelligent microfluidic manipulator (Fig. 8(e)) capable of sensing fluid temperature and sorting droplets via active deflection.

4.2.2 Humidity-response actuation

Humidity-driven helical actuators convert hygroscopic swelling into mechanical work. A major mechanism involves anisotropic swelling in twisted fibers or yarns: radial expansion upon moisture absorption is geometrically converted into axial contraction or rotation [131]. For instance, silk-based muscles have achieved contraction strokes up to 70% [132], while recent composite designs that introduce inter-bundle anchoring mitigate twist instability and reach high static stability (97.5%) [133]. Fibers can also be engineered into two-ply coils [134] with tailored chirality (Fig. 8(h)). Beyond reversible actuation, hair-based systems can be programmed into irreversible modes as one-time fuses or moisture alarms. As shown in Figs. 8(i) and 8(j), homochiral coils function as visual hygrometers, whereas heterochiral coils enable reversible shape changes, such as smart hairstyles that contract upon wetting and recover after drying. Notably, humidity actuation can be scaled to fabric-level systems [135]. For example, smart textiles woven from cotton and twisted fibers provide actuation coupled with real-time visual feedback, where cobalt–alginate fibers change color during deformation, enabling camouflage and environmental indication.

Alternatively, humidity actuation can be bending-dominated, driven by asymmetric swelling in bilayer or gradient architectures. In such systems, differential expansion between an active hygroscopic layer and a passive layer generates an internal bending moment that drives curling or straightening [136]. Recent MXene-based soft composites and modified silk hierarchies have achieved high sensitivity and fast response (e.g., 0.3 s response for MXene films and a $7.06\text{ cm}^{-1}\cdot\text{s}^{-1}$ bending rate for silk structures), enabling autonomous soft robots that crawl directionally under ambient moisture gradients without external power sources [137].

4.2.3 Electrochemical actuation

Electrochemical helical actuators operate through reversible ion intercalation and de-intercalation in electroactive matrices, such as conducting polymers or carbon nanotubes, under low voltages. While the intrinsic volume change from redox reactions is often limited and quasi-isotropic, twisted and coiled architectures can amplify this microscopic swelling into macroscopic stroking or torsional rotation [138, 139]. Recent work has further integrated force-sensing based on electrochemical double-layer capacitance changes, enabling closed-loop control for robotic grasping [138]. Such structural conversion allows electrochemical artificial muscles to reach stress levels beyond those of natural skeletal muscle. For example, coiled conducting polymer yarns can deliver large contractile strokes driven by ion-doping-induced volume expansion [30]. Pure PEDOT:PSS yarn muscles have also been reported as a cost-effective route by eliminating carbon nanotubes while maintaining high performance, achieving output stresses of approximately 5 MPa and lifting loads over 4000 times the yarn weight. To further improve response speed and strain amplitude, hierarchical architectures and optimized composites have been developed, enabling sub-second and high-strain actuation suitable

for dynamic tasks [140]. Beyond single fibers, the mechanical robustness of electrochemical helical yarns allows industrial knitting and textile processing, enabling electrically controlled morphing textiles [141]. Sheath-core designs that support meter-scale continuous production further bridge laboratory prototypes and scalable wearable implementations.

4.3 Energy

4.3.1 Energy harvesting

The helical structure intrinsically exhibits a spring-like mechanical response, allowing the material to withstand large tensile, compressive, and bending deformations without structural failure.

In addition, helical fibers experience amplified mechanical deformation under cyclic loading and owing to their ability to accommodate multidirectional motions arising from human activities or environmental perturbations, they display markedly enhanced sensitivity to variations on mechanical stimuli. These attributes confer impact significant advantages for triboelectric nanogenerators (TENGs), as they facilitate greater contact-separation dynamics and enable more efficient conversion of irregular mechanical energy into electrical output.

TENGs have attracted extensive interest because of their lightweight form factor, low cost, and high conversion efficiency. However, conventional thin-film triboelectric devices often suffer from mechanical fragility, leading to cracking and performance

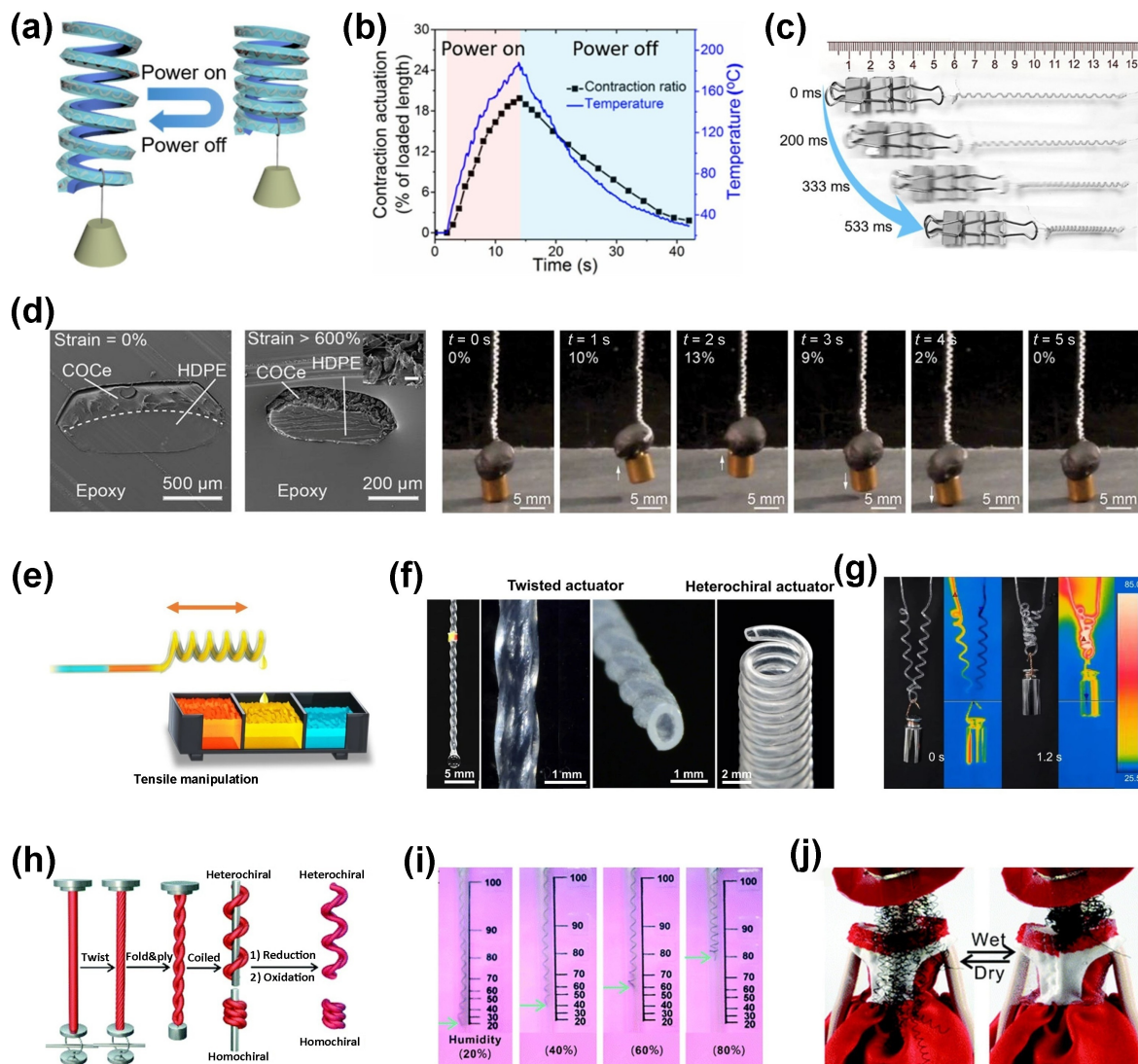


Figure 8 (a) The schematic diagram of the conductive tendril working as reversible contraction actuator under electric power with loading, (b) the contraction ratio and temperature change of the conductive tendril during power on and off, and (c) the elastic dragger pulled the load forward by 4.5 cm within 533 ms on ground. Reproduced with permission from Ref. [20], © American Chemical Society 2018. (d) Cross-sectional scanning electron microscope (SEM) images of a fiber before and after cold drawing and a photographic time series collected during a vertical lift experiment. Reproduced with permission from Ref. [23], © Kanik, M. et al. 2019, some rights reserved; exclusive licensee American Association for the Advancement of Science. (e) Schematic of the tensile hollow-fibre actuator used for sensing the liquid temperature and sorting the liquid into the desired cell, (f) images of the coiled and twisted hollow-fibre actuators, and (g) optical and infrared images of a PEHF₃₈₀₋₉₉₀ actuator lifting a 10-g load in 1.2 s when flowing 90 °C water. Reproduced with permission from Ref. [130], © Li, S. T. et al. 2025. (h) Schematic illustration of the fabrication of the two-plyed tensile hair artificial muscles with homochiral and heterochiral coils, (i) sequential photos showing a hygrometer made of homochiral hair artificial muscles, which changed length with change in ambient humidity, and (j) photographs of a doll with a “smart hair style” that can contract upon exposure to water droplets and return back after drying. Reproduced with permission from Ref. [134], © The Royal Society of Chemistry 2021.

degradation under repeated dynamic loading. Mao et al. [142] developed a DNA-helix-structured kirigami nanogenerator (DSKN) with improved durability and output stability. The device maintained a stable electrical output with a peak power density of $1.3 \text{ mW} \cdot \text{cm}^{-3}$ after 108,000 compression-release cycles. To improve multimodal energy harvesting under large deformation, Wu et al. [17] proposed a helically structured core-shell TENG (HS-TENG) (Fig. 9(a)), which generates electrical output through coupled contact electrification and electrostatic induction under pressing (Fig. 9(b)). Benefiting from its core-shell helical configuration, the device tolerates large stretchability (up to $\sim 200\%$ strain) and can convert diverse mechanical inputs, including pressing, bending, stretching, and twisting into electrical outputs. The HS-TENG achieved a maximum output power of $4.2 \mu\text{W}$ at a load resistance of $50 \text{ M}\Omega$ under a pressing frequency of 1 Hz (Fig. 9(c)).

Helical yarns naturally arise from twisted filament assemblies and provide a textile-compatible route toward wearable TENG systems [143]. Fu et al. [113] fabricated liquid-metal-based double helix core-spun yarns that combine mechanical stretchability with wearing comfort and can be woven into plain fabrics using standard textile equipment. The yarn delivered a peak output power

of $5 \mu\text{W}$ at $100 \text{ M}\Omega$, suggesting feasibility for driving low-power wearable functions when integrated with appropriate power-management modules. In addition, Cho et al. [14] reported a multimodal TENG based on MXene-reinforced spiral yarns, where the bioinspired helical architecture enables conformal wrapping on curved surfaces or soft tissues, facilitating seamless integration into wearable platforms. The yarns were further assembled into textile-based interactive interfaces, such as tactile arrays for password recognition and smart gloves for virtual instrument control, illustrating the system-level utility of helix-enabled textile integration.

Thermoelectric generators (TEGs) harvest electricity from temperature gradients and are promising power sources for wearables. However, wearable TEGs devices typically need to sustain strains exceeding $\sim 30\%$ to accommodate deformations induced by daily motion. Helical designs have therefore been introduced to impart stretchability and mechanical compliance while preserving thermoelectric pathways. Xu et al. [145] developed a facile template-assisted strategy to fabricate three-dimensional helical inorganic TEGs using a screw as a mold. The resulting devices exhibited high stretchability ($\sim 100\%$ strain), mechanical

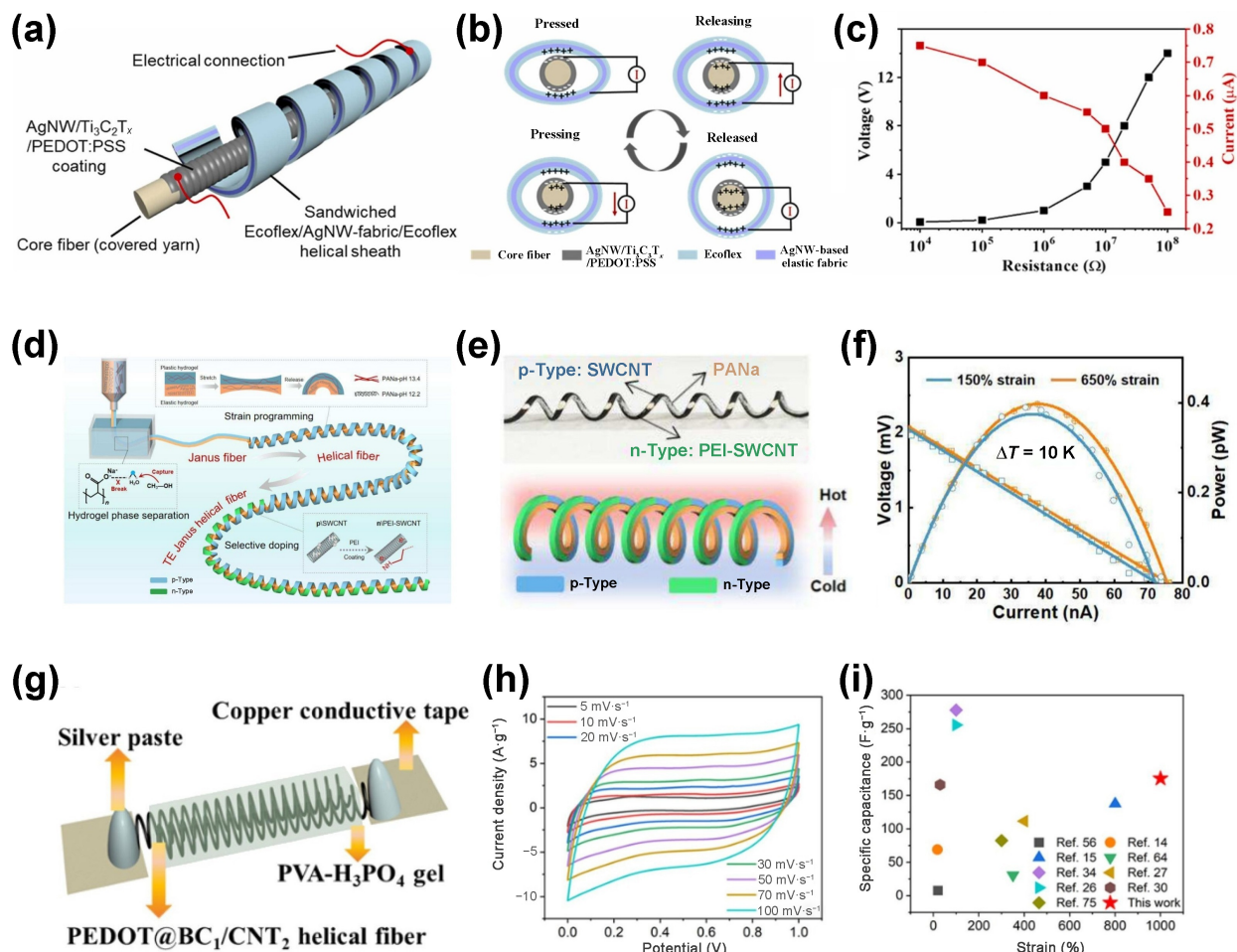


Figure 9 (a) Schematic illustration of the structure of the HS-TENG, (b) schematic illustration of the working principle of the HS-TENG, and (c) the variation of V_{OC} , I_{SC} of the HS-TENG with different external load resistance. Reproduced with permission Ref. [17], © Elsevier Ltd. 2022. (d) Schematic illustration for the design and preparation of thermoelectric Janus helical hydrogel fibers. TE: thermoelectric. (e) Photograph (top) and schematic of the p/n Janus helical hydrogel fiber for thermal energy harvesting through out-of-plane temperature gradient (bottom) and (f) thermoelectric performances of the Janus helical fiber at 150% and 650% strains under a ΔT of 10 K . Reproduced with permission Ref. [18], © American Chemical Society 2025. (g) Schematic of the self-stretchable PEDOT@BC₁/CNT₂ hybrid helical fiber supercapacitor's structure, (h) CV curves of the supercapacitors at various scan rates, and (i) comparison of the gravimetric specific capacitance and the strain for the self-stretchable helical fiber supercapacitor and the other reported supercapacitors. Reproduced with permission from Ref. [144], © Elsevier B.V. 2021.

stability over 1000 cycles, and lightweight characteristics, delivering an open-circuit voltage up to 32 mV and a maximum power density of $\sim 42 \text{ nW}\cdot\text{g}^{-1}$ under a temperature difference of 50 K. To further improve robustness and strain tolerance, Wang et al. [18] reported Janus helical hydrogel fibers (Fig. 9(d)) that retained their intrinsic thermoelectric performance under ultrahigh elastic deformation, with a fracture strain up to 1700%. The structure and working mechanism are illustrated in Fig. 9(e). The system achieved an output power density of $6.5 \text{ mW}\cdot\text{cm}^{-2}$ and a peak output voltage of 10 mV, and it could sense ambient temperature variations with a sensitivity of $-176 \mu\text{V}\cdot^\circ\text{C}^{-1}$ (Fig. 9(f)).

Beyond TENGs and TEGs, helical fiber-based harvesters have also been developed using alternative transduction mechanisms. Kim et al. [146, 147] reported an energy harvester based on twisted and coiled carbon-nanotube yarns that electrochemically convert tensile or torsional mechanical energy into electricity. The yarns withstand high reversible strains and achieved a peak power density of $250 \text{ W}\cdot\text{kg}^{-1}$, demonstrating applicability in harvesting low-frequency ocean-wave energy and powering LED lights.

4.3.2 Energy storage

Wearable energy-storage units must also maintain reliable operation under complex deformation, motivating intrinsically stretchable architectures that decouple electrochemical performance from external strain [148]. Liang et al. [144] fabricated PEDOT@BC/CNT hybrid helical fibers via a combined wet-

spinning and coiling process (Fig. 9(g)). The substrate-free helical architecture imparted intrinsic self-stretchability, enabling an ultrahigh fracture strain up to 1175%. As shown in Fig. 9(h), the cyclic voltammetry curves retained an almost ideal rectangular shape across a wide range of scan rates, indicating favorable rate capability and fast ion-transport kinetics. Notably, both the capacitance retention and the stretchability exceeded those of many recently reported stretchable fibrous supercapacitors (Fig. 9(i)), highlighting the potential of helix-enabled structures for mechanically robust energy storage in wearable systems.

4.4 Filtration and separation

4.4.1 Air filtration

Helical fibrous architectures provide distinct structural advantages for air filtration. As illustrated in Fig. 10(a), their three-dimensional (3D) coiled morphology facilitates the construction of hierarchical porous networks, thereby regulating airflow pathways and particle-transport behavior. Compared with straight-fiber media (Fig. 10(b)), helical fibers typically introduce higher pore tortuosity and prolong the effective residence time of air within the filter, which strengthens multiple capture mechanisms, including inertial impaction, interception, and Brownian-diffusion-driven deposition on fiber surfaces. Meanwhile, the open and 3D-interconnected pore architecture can promote airflow redistribution and mitigate localized flow constriction, which helps reduce pressure drop

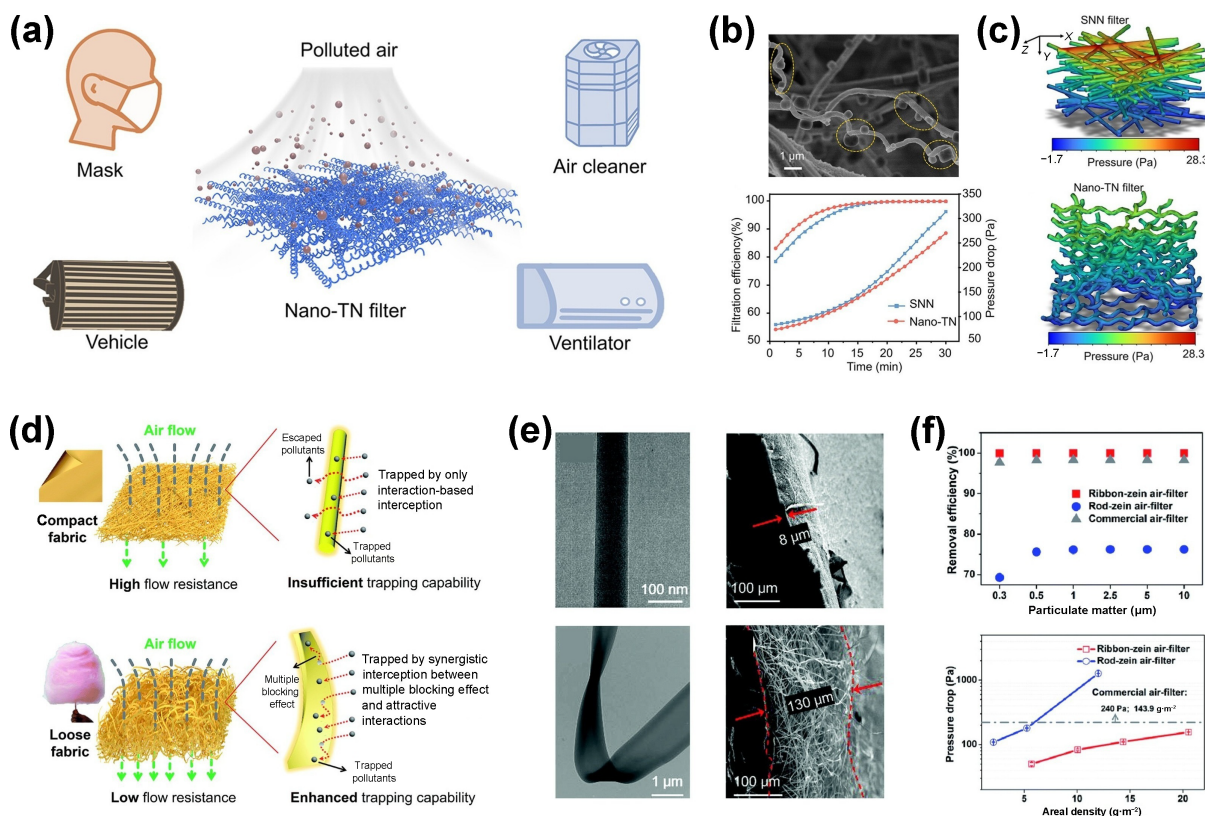


Figure 10 (a) Schematic illustration of nanoscaled tendril nonwoven filtering particulate matter and its potential application fields in personal protection, air purification, and vehicles, (b) SEM image of nanoscaled tendril nonwovens after PM filtration and long-term filtration loading test of nanoscaled tendrils and straight nanofibers and (c) diagram of pressure distribution when the airflow passes through straight nanofibers and helical nanofibers. Reproduced with permission from Ref. [9], © American Chemical Society 2024. (d) The differences between the straight rod and self-curved ribbon of zein fabrics in flow resistance and trapping capability of air pollutants, (e) TEM images and SEM images of the rod-zein and self-curved ribbon fiber, and (f) the PM removal efficiencies of the ribbon-zein, rod-zein and a commercial air-filter, the dependence of pressure drops on areal density for the ribbon-zein and rod-zein fabrics. Reproduced with permission from Ref. [149], © The Royal Society of Chemistry 2018.

(Fig. 10(c)). As a result, filters based on helical fibers can achieve improved capture of submicron particles while maintaining favorable permeability (Table 3).

Representative systems demonstrated how curvature enabled pore architectures translate into device-level gains. Fan et al. [149] reported a multifunctional protein-based fabric composed of self-curling ribbon like fibers, with the fabrication strategy shown in Fig. 10(d). The self-curved ribbon fibers stack into a loosely packed architecture with a high porosity of 83%, in contrast to the compact sheets formed by conventional rod-shaped zein fibers (Fig. 10(e)). Benefiting from this open porous configuration, the ribbon-zein fabric achieved a particulate matter (PM) removal efficiency of 99.9% with a reduced pressure drop of 107 Pa (Fig. 10(f)), corresponding to only ~ 8% of that of the rod-zein counterpart. Although curved or crimped morphologies have been widely explored to enhance filtration efficiency, there remains substantial room to further lower airflow resistance while maintaining high capture efficiency, especially under practical loading conditions. To address both filtration performance and mechanical robustness, Li et al. [150] developed superelastic and mechanically robust electrospun nanofibrous aerogels (NFAs) for ultrafine and nanoscale particle filtration. Their semi-interpenetrating polymer network (semi-IPN)-based gradient NFAs exhibited temperature invariant superelasticity, high compressive stress (7.9 kPa) and modulus (12 kPa), exceptional filtration efficiency (> 99.97% for 0.3 μm particles), and an ultrahigh dust-holding capacity of 114 $\text{g}\cdot\text{m}^{-2}$. Li et al. [151] further designed ultrafine, curly, wool-like nanofibers (termed “nano-wool”) via a one-step strategy. The nano-wool forms a fluffy assembly and exhibited a strong electret effect with a high surface potential of 13,260 V. Its high porosity (98.7%) is attributed to the spatial support provided by self-crimped nanofibers, enabling a filtration efficiency of > 99.995% for 0.3 μm particles at a low pressure drop of 55 Pa. In addition, Zhu et al. [152] fabricated a 3D nanofiber sponge featuring curly fibers, layered pores, and low density by controlling the humidity during spinning, achieving > 98% filtration efficiency for 0.3 μm particles while maintaining a pressure drop of approximately 56 Pa.

Beyond PM, gaseous hazards such as formaldehyde, a prevalent indoor and in-vehicle pollutant, also threaten public health. Zhang et al. [153] employed a bi-solvent electrospinning strategy to fabricate self-curved ribbon-like fibers from zein/ZIF-8 solutions, followed by solvent-fumigation welding to reinforce membrane integrity. The resulting membrane consists of self-curved ribbon-like nanofibers that assemble into a 3D fluffy, hierarchical porous architecture with

increased surface roughness. The membrane delivered an overall performance of 99.04% PM_{2.5} removal with a low pressure drop of 54.87 Pa, and additionally achieved 98.8% formaldehyde removal together with photocatalytic antibacterial activity.

Despite these advances, many bioinspired helical-fiber filters still achieve high performance at the expense of increased thickness, which increases bulkiness and limits their applicability in lightweight and wearable filtration systems. To address this limitation, Zhao et al. [9, 82] fabricated bioinspired helical nanofiber filter fabrics with significantly increased curvature. Because highly coiled fibers can pack into porous networks with efficient structural utilization, the resulting assemblies can maintain high filtration efficiency (81%) for fine particles while exhibiting low airflow resistance (56.8 Pa), even without a substantial thickness increase. In addition, compared with straight fiber filters, the helical fiber filters demonstrated markedly enhanced dust-holding capacity (4.1 $\text{g}\cdot\text{m}^{-2}$), which is favorable for extended service lifetime and improved operational stability.

In addition to the previous studies, Li et al. [155] conducted an integrated integration that combines experimental measurements with numerical simulations. In this work, the generation of accurate nonwoven filter geometric models were developed and integrated with computational fluid dynamics (CFD) simulations to predict filtration performance, with a focus on filters composed of helical structured fibers. The helical curvature of fibers plays a significant influence in filtration performance. Specifically, filters constructed from fibers with higher helical curvature exhibit lower pressure drop and higher dust-holding capacity, indicating that fiber geometry strongly influences flow resistance and particle capture efficiency.

4.4.2 Adsorption and separation

Helical fibrous architectures offer distinctive advantages for adsorption and separation by combining hierarchical porosity, enlarged accessible surface area, and mechanically resilient 3D frameworks. Compared with straight-fiber counterparts, helically coiled fibers can simultaneously introduce abundant intra-fiber pores and additional inter-fiber cavities created by the coiled configuration, thereby providing enlarged storage/transport space, reduced flow resistance, and improved structural recoverability under compression. These features make helical fibrous materials particularly attractive for pollutant removal from water, including oils, organic dyes, and heavy-metal species [156, 157].

Oil sorption and retention. Zhao et al. [158] employed a bioinspired coaxial electrospinning strategy to fabricate porous

Table 3 Filtration performances of helical structure-based fiber filters

Filter type	Filtration performance (%)	Pressure drop (Pa)	Key parameters	Refs.
PAN curly nanofibers	98.30 for PM _{0.3}	~ 59	Quality factor: 0.0700, thickness: 55mm, thermal conductivity: 0.032 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	[152]
PMIA/TPU helical nanofibers	91.70 for PM _{0.3}	~ 55	Quality factor: 0.0450, thickness: 15 μm , self-extinguishing	[82]
CA/TPU helical nanofibers	83.20 for PM _{0.3}	~ 57	Quality factor: 0.0310, thickness: 30–50 μm	[9]
Zein@ZIF-8 self-curved fibrous membrane	96.02 for PM _{2.5}	~ 37	Quality factor: 0.0872, thickness: 0.4 mm, formaldehyde removal efficiency: 98.8 %	[153]
Superflexible nanofibrous aerogels	99.97 for PM _{0.3}	~ 189	Quality factor: 0.0429, thickness: 13.6 mm, antibacterial and antiviral function	[154]
Wool-like nanofibers	99.99 for PM _{0.3}	~ 55	Quality factor: 0.1675, thickness: 211 μm	[151]
PAI/BMI semi-interpenetrating fibrous aerogels	99.98 for PM _{0.3}	~ 211	Quality factor: 0.0404, dust-holding capacity: 114 $\text{g}\cdot\text{m}^{-2}$	[150]
Spring-like ribbon-zein fibers	99.90 for PM _{0.3}	~ 107	Quality factor: 0.0646, thickness: 130 μm	[149]

PVDF/PS core-shell helical fibers (Fig. 11(a)), where the solvent-evaporation rate was tuned to introduce intra-fiber porosity. Compared with conventional straight fibers, the porous helical fibers possessed not only abundant internal pores but also additional inter-fiber cavities arising from the intrinsic coiled geometry, providing efficient storage space for crude-oil sorption (Fig. 11(b)). As a result, the PS/PVDF porous helical fibers exhibited dual advantages of high sorption capacity and high retention stability, achieving oil uptake of approximately 37–69 times their own weight. Teng et al. [159, 160] further fabricated helical ribbon fibers via bicomponent electrospinning of a zein/PVDF composite. The resulting fibers displayed a hierarchical helical-ribbon morphology with grooved surfaces

(Fig. 11(c)). The PVDF component mitigated the brittleness of pure zein and improved mechanical flexibility. Compared with pure zein fibers, the zein/PVDF helical ribbon fibers showed a 75% enhancement in oil-retention capability (Fig. 11(d)). The reusability was validated over five sorption/desorption cycles, with only a slight decrease in sorption capacity from 37 to 31 $\text{g}\cdot\text{g}^{-1}$, indicating that helicity and hierarchical geometry play a key role in stabilizing oil storage and preventing dripping. To overcome the poor mechanical robustness typical of nanofibrous sorbents, Teng et al. [157] also developed a co-electrospinning strategy using different spinneret configurations to produce TPU/Nomex-based helical nanofibers with tunable curvature. The introduction of 3D helical geometry markedly enhanced stretchability, with a tensile strain of up to 76%.

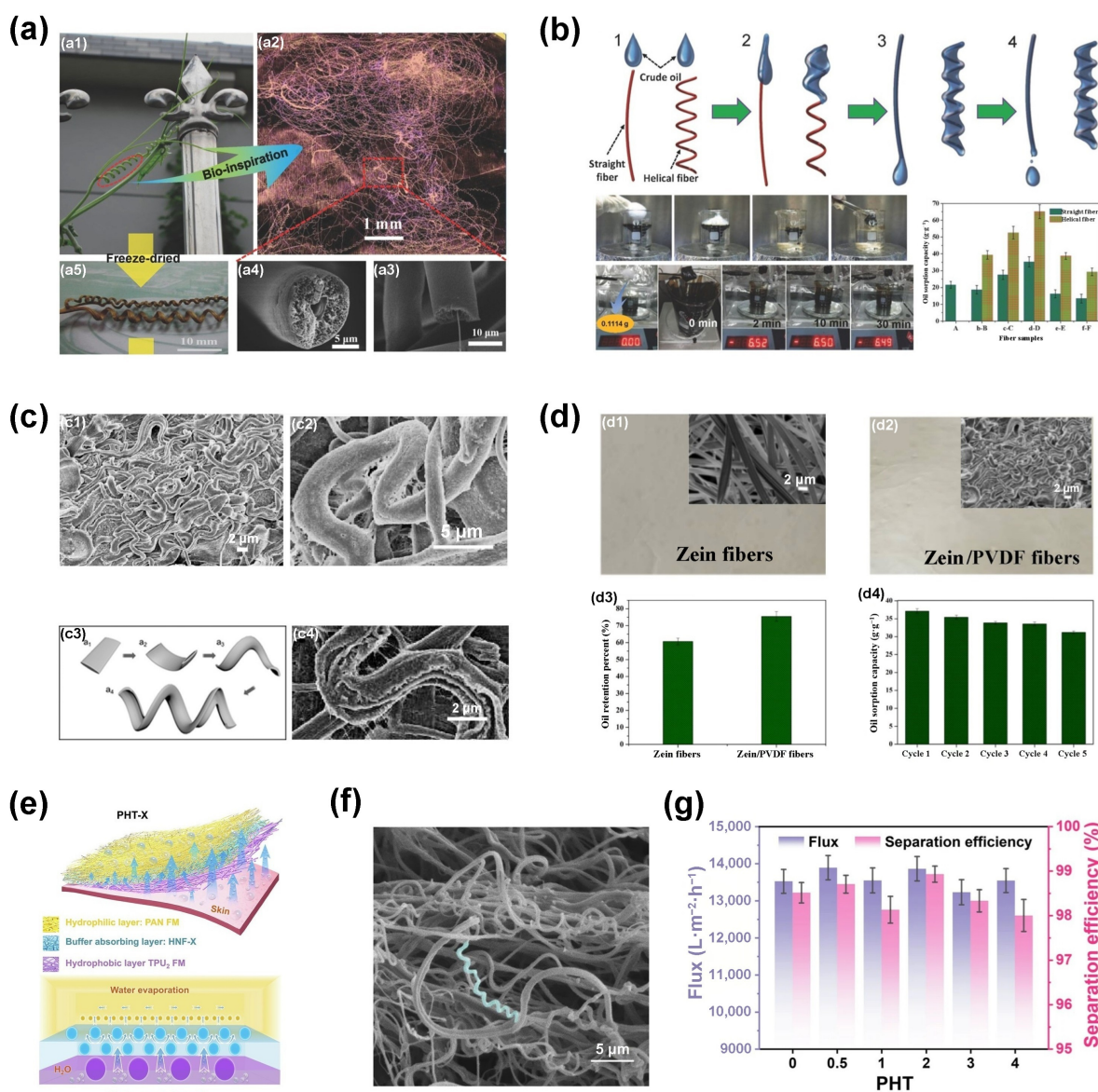


Figure 11 (a) The parasitic coiled tendrils of young loofah vine and cross-sectional and flank-fractured SEM images of the helical porous fibers, (b) sorption of crude oil by the helical porous fibers. Reproduced with permission from Ref. [158], © Zhao, Y. Y. et al. 2017. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (c) SEM images of zein/PVDF fibers prepared by bicomponent electrospinning and schematic representation of helical ribbon structural evolution process, (d) photographs of the zein fiber mat and the zein/PVDF fiber mat, inserted with their SEM images, oil retention percentage of the zein fibers and zein/PVDF fibers and oil sorption capacity of the zein/PVDF fibers during five consecutive sorption/desorption cycles. Reproduced with permission from Ref. [159], © Elsevier 2020. (e) Schematic diagram of PHT-X Janus fiber membrane and the water ascent channel path and gradient aperture of the PHT Janus fiber membrane generating higher capillary forces, spontaneously absorbing water upward, (f) SEM images of HNF-2 membranes and (g) Separation efficiency and flux of PHT-X-Janus fiber membrane. Reproduced with permission from Ref. [7], © Kuang, X. J. et al. 2025.

Meanwhile, these fibers delivered an exceptional oil sorption capacity of $79.3 \text{ g}\cdot\text{g}^{-1}$ and a high retention ratio of 91%, effectively suppressing oil dripping during handling.

Adsorption of hazardous chemicals. Beyond oil removal, helical fibrous materials also show promise for capturing hazardous substances, including toxic organic compounds and emerging contaminants. Wang et al. [161] prepared helical carbon fibers via a bio-template route, producing sorbents with an ultrahigh specific surface area and a high fraction of 1–3 nm pores (> 80% of total pore volume). The resulting helical carbon fibers achieved a specific surface area of $3089 \text{ m}^2\cdot\text{g}^{-1}$ and exhibited a high sulfamethoxazole adsorption capacity of $1091 \text{ mg}\cdot\text{g}^{-1}$ with a rapid equilibrium time of ~ 30 min, outperforming many conventional carbon adsorbents. These results highlight how helix-enabled high-accessibility microporosity can simultaneously enhance adsorption capacity and kinetics.

Oil/water separation under harsh conditions. Helical architectures can further serve as mechanically robust frameworks for oil/water separation, especially under harsh conditions involving repeated compression, structural deformation, or long-term cycling. Yang et al. [162, 163] developed superhydrophobic composites by weaving stainless-steel helical wires nested with cotton fibers into a macro-micro composite framework, followed by surface modification to impart superwetting properties. The resulting membrane achieved separation purities up to 99.98% under complex conditions, and maintained stable flux and separation efficiency after 500 compression cycles, indicating that the mechanically robust helical metal skeleton enables durable and reliable separation performance. In addition, Li et al. [16] obtained resilient helical carbon nanofibers via chemical vapor deposition. Benefiting from the 3D helical geometry, the material exhibited strong compressive resilience and enabled efficient oil/water separation.

Directional liquid transport. In addition to sorption and oil/water separation, helical fibers can facilitate directional liquid transport by reducing transport resistance and enhancing pore interconnectivity. Kuang et al. [7] developed a biomimetic Janus membrane by integrating a 3D helical nanofibrous intermediate layer, enabling directional liquid transport driven by synergistic wettability and pore-size gradients (Fig. 11(e)). Compared with straight-fiber interlayers, the helical intermediate layer increased porosity and lateral connectivity, thereby minimizing transport resistance and facilitating rapid permeation (Fig. 11(f)). Consequently, the Janus membrane achieved a unidirectional transport index of 1250% and a separation efficiency of 98.92%, with an ultrahigh flux of $13,860.77 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ (Fig. 11(g)).

4.5 Thermal and microwave management

4.5.1 thermal insulation

Helical fibrous architectures offer advantages for thermal management by engineering heat and mass transport pathways within a three-dimensional (3D) porous network. Their coiled geometry can elongate and diversify solid heat-conduction paths by reducing effective contact area and increasing tortuosity, create numerous enclosed pockets that suppress gas convection, and enhance multi-scattering and reflection of thermal radiation within hierarchical pores.

Yang et al. [92] fabricated superelastic and washable spring-like PVDF nanofibrous sponges by manipulating charge density and

phase separation (Fig. 12(a)). Owing to fiber stacking and entanglement within the coiled network, the PVDF sponge tolerated large tensile deformation (up to 50% strain) with rapid pitch recovery upon release, as evidenced by in situ dynamic microscopic observations (Fig. 12(b)). Notably, the sponge maintained a low thermal conductivity of $24.85 \text{ mW}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ even under high humidity and repeated compression, demonstrating strong environmental adaptability and washability (Fig. 12(c)). To further reduce weight while retaining warmth, Wang et al. [164] tuned the density of helical-fiber aerogels to obtain highly porous and ultralight PS/PU fibrous aerogels. The aerogel exhibited a low thermal conductivity of $24.5 \text{ mW}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, outperforming commercial down feathers, together with an ultralow density of $6.8 \text{ mg}\cdot\text{cm}^{-3}$ and near-complete recovery after 1500 deformation cycles. In a related effort, Wang et al. [165] also employed multi-jet electrospinning to fabricate ultralight polyimide (PI) curly nanofiber aerogels with an interlocked 3D network, ultrahigh porosity (99.8%), and a small pore size ($\sim 1.57 \mu\text{m}$). Such microstructural features effectively suppress long-range air movement and minimize solid conduction, enabling a low density of $2.4 \text{ mg}\cdot\text{cm}^{-3}$ and thermal conductivity of $22.4 \text{ mW}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. Benefiting from the intrinsic thermal stability of PI, the aerogel retained superelasticity and structural integrity across an extreme temperature window (-196 to 300°C).

Beyond material design, scalable production of helical/curly fibers is critical for practical warm-retention textiles. Airflow-assisted electrospinning and related turbulence-driven processes can increase throughput by providing strong drawing forces and stabilizing fiber formation. Cheng et al. [91] developed a grid-induced homogeneous turbulence spinning (GHTS) system that uses high-speed airflow and grid-generated vortices to efficiently fabricate highly curved PVB nanofibers (HCNFs). The resulting curly network forms abundant enclosed or semi-enclosed still-air pockets (Fig. 12(d)), enabling comprehensive suppression of heat transfer by extending solid conduction paths, obstructing convection, and enhancing radiative scattering. Field tests validated its cold-protection capability: in extreme environments (e.g., -28°C) and comparative tests at -20°C , an 8.9 mm-thick HCNF garment maintained a body temperature of 29.72°C , matching the warmth of an 18.45 mm-thick goose-down jacket and significantly outperforming a cotton garment of comparable thickness (Figs. 12(e) and 12(f)). Furthermore, Yu et al. [90] reported a turbulence-driven, orifice-free melt-blowing strategy in which rotating-mesh-induced vortices refine molten PP into highly curled nanofibrous sponges, improving thermal-insulation efficiency from 0.257 to $0.53 \text{ clo}\cdot\text{mm}^{-1}$ relative to goose down garment.

To expand the application space toward extreme thermal environments, helical structures have also been implemented in ceramic and oxide nanofibrous aerogels. Dang et al. [93] employed a two-component off-axial electrospinning strategy to produce ultrastretchable ceramic aerogels composed of highly buckled nanofibers. In situ SEM observations revealed that massive deformation is accommodated primarily through untwisting and alignment, allowing the aerogel to sustain dynamic stretching under a 1000°C flame without structural failure (Figs. 12(g) and 12(h)), thereby enabling tensile-insensitive thermal insulation. Such performance, combined with robust stretchability, supports applications under severe service conditions, for example as insulating layers for morphing aircraft exposed to high-temperature aerodynamic heating (Fig. 12(i)). In addition, Zhao et al. [166]

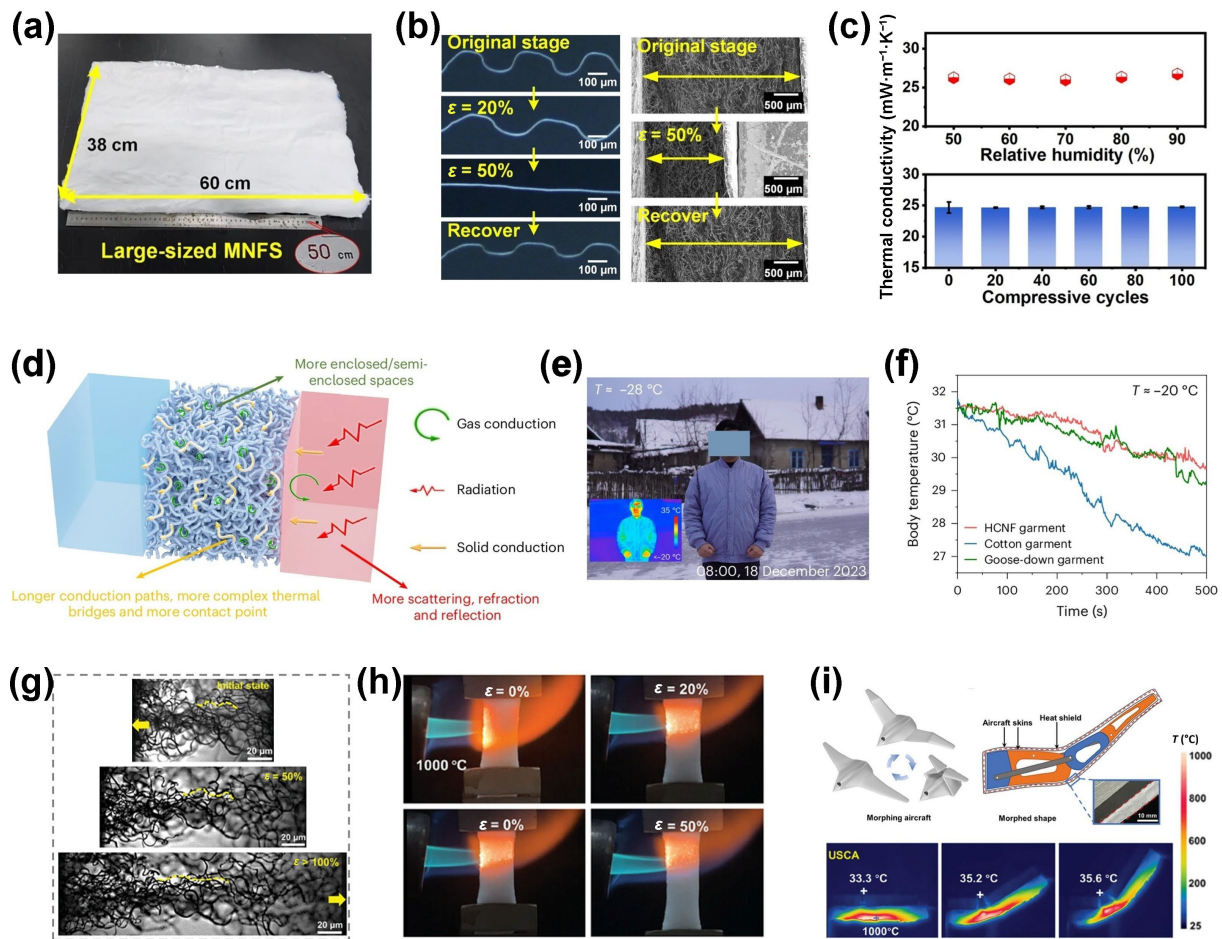


Figure 12 (a) Large-sized of MNFS, (b) Stretch-recovery behavior of helical fiber and compressive-recovery behavior of MNFS observed via in situ SEM, and (c) thermal conductivity of MNFS under the environment with diverse relative humidity (top) and various compression cycles (bottom), respectively. Reproduced with permission from Ref. [92], © Yang, F. J. et al. 2025. (d) By inhibiting heat conduction, radiation and convection through the curled nanofibrous structure, HCNFs effectively inhibit heat loss from high temperatures (red zone) to low temperatures (blue zone), (e) optical image (and infrared thermogram, inset) of an individual wearing the HCNF garment at a temperature (T) of around $-28\text{ }^{\circ}\text{C}$ in a high-latitude region (53.5°N), showing the thermal resistance of the garment, and (f) experimental configuration at around $-20\text{ }^{\circ}\text{C}$, with temperature sensors embedded in an 8.90-mm-thick HCNF garment, a 9.00-mm-thick cotton garment, and an 18.45-mm-thick 850-FP goose-down garment. Reproduced with permission from Ref. [91], © Springer Nature 2025. (g) Microstructure evolution of USCA during uniaxial tension by in situ SEM, (h) tension and recovery process under 50% strain with the heat of a butane blowtorch flame, and (i) illustration of a morphing aircraft, structure of morphing wing and thermal insulating performances of USCA. Reproduced with permission from Ref. [93], © Wiley-VCH GmbH 2024.

fabricated a dual-oxide nanofibrous aerogel based on curved-fiber design, offering an integrated platform for extreme thermal protection ($7\text{ mW}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) while coupling flame retardancy, noise absorption, and catalytic conversion.

4.5.2 microwave absorption

With the intensification of electromagnetic pollution, helical structures such as carbon nanocoils (CNCs) and chiral conducting polymers have attracted significant attentions as high-performance microwave absorbers. Their advantages originate from a combination of chirality-enabled cross polarization and polarization conversion, which can introduce additional magnetic-type loss pathways and enhance wave dissipation without relying solely on heavy magnetic fillers; and a three-dimensional (3D) spiral morphology that elongates the propagation path of incident waves through multiple reflections and scattering within hierarchical voids.

Wang et al. [167] employed atomic layer deposition (ALD) to coat CNCs with conformal magnetic layers, constructing coaxial

multilayer nanostructures (Fig. 13(a)). This core-shell design leverages the complementary regulation of complex permittivity and permeability to improve impedance matching, thereby enhancing microwave absorption. In parallel, Zuo et al. [168] proposed a phase-engineering strategy that regulates the amorphous/crystalline carbon ratio in CNCs via high-temperature annealing (Fig. 13(b)). The optimized phase distribution strengthens interfacial polarization and relaxation losses along the helical conductive pathways, enabling a better balance between conduction loss and polarization relaxation. The optimized CNCs achieved an RLmin of -49.2 dB and an effective absorption bandwidth (EAB) of 6.0 GHz at a thin thickness of 1.9 mm . To further reduce weight and alleviate impedance mismatch associated with highly conductive carbon, Zuo et al. [169] introduced micro-mesopores and oxygen doping into the CNC framework through air oxidation. The porous helical network promotes multiple scattering, while dipole polarization is tuned to mitigate impedance mismatch, at a low loading of $3\text{ wt.}\%$, the material delivered a wide EAB of 7.3 GHz . Beyond carbon helices, Li et al. [170] constructed

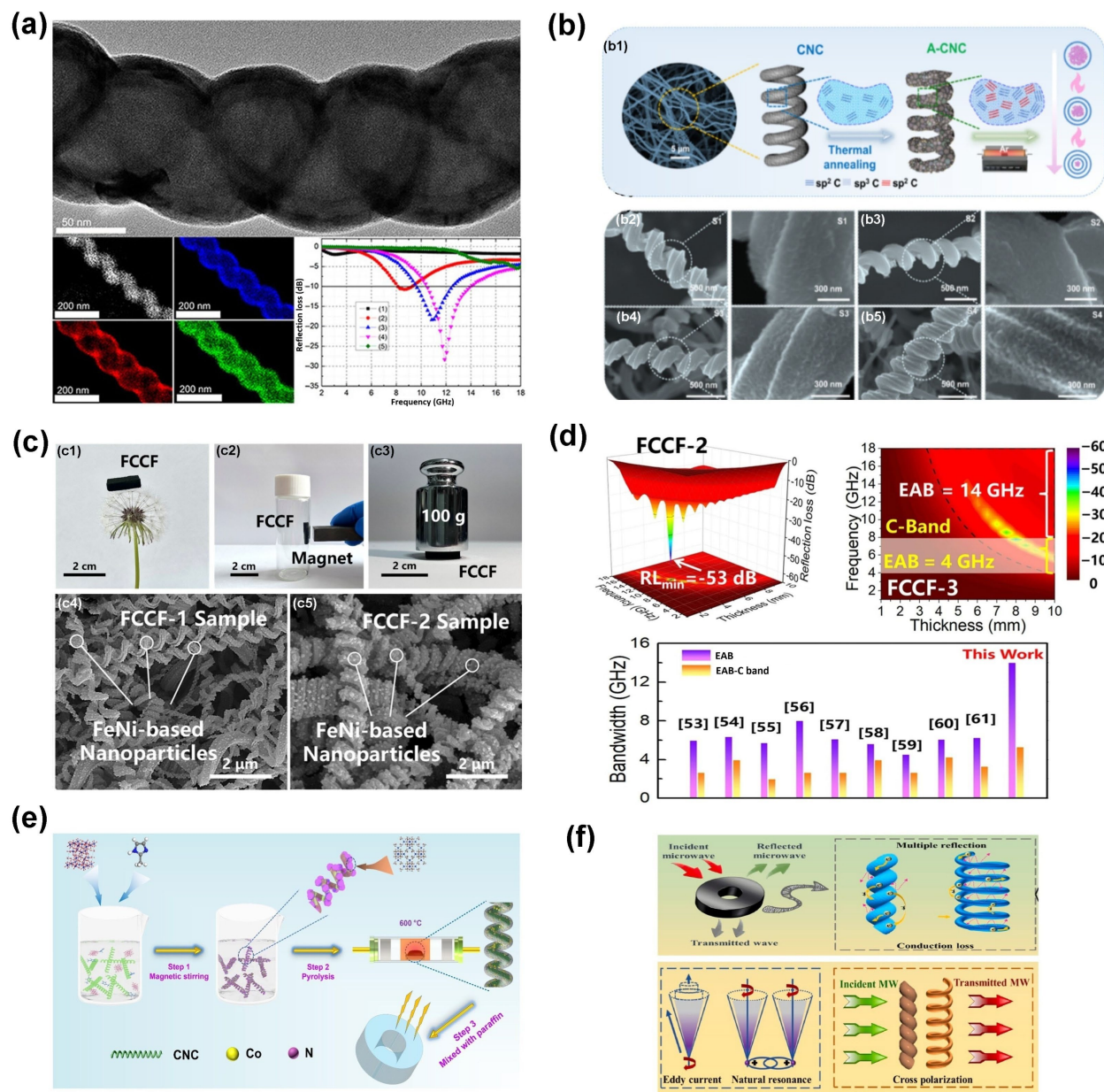


Figure 13 (a) TEM and elemental mapping images of the $\text{Fe}_3\text{O}_4/\text{Al}_2\text{O}_3/\text{CNC}$, and microwave RL curves of the product/paraffin composites with a thickness of 2 mm in the frequency range of 2–18 GHz. Reproduced with permission from Ref. [167], © American Chemical Society 2012. (b) Schematic illustration of CNCs formation with different sp^2/C ratio and SEM images. Reproduced with permission from Ref. [168], © Elsevier B.V. 2025. (c) Images of optical, magnetic properties, structural robustness of the FCCF, and SEM images of the FCCF, (d) 3D RL value of the FCCF-2 sample, projection plot of the FCCF-3 sample and the bandwidth comparisons between the FCCF and previous works. Reproduced with permission from Ref. [171], © Zhang, H. et al 2025. (e) Schematic illustration for the formation of the Co@N-Carbon/CNCs composites. Reproduced with permission from Ref. [172], © Elsevier Inc 2021. (f) MA mechanism of the TCNFs and SCNFs. Reproduced with permission from Ref. [16], © Elsevier Ltd. 2024.

multistage helical nano/microstructures based on chiral polyaniline and helical polypyrrole (PPy) via in situ polymerization. By leveraging multiscale chiral synergy, the hierarchical architecture strengthens cross-polarization and prolongs attenuation pathways within spiral voids, achieving a minimum reflection loss ($\text{RL}_{\min}$) of -51.3 dB and a broad EAB of 8.6 GHz (7.4–16 GHz) at a thickness of 3.6 mm.

After achieving effective absorption in conventional higher-frequency bands, research has increasingly shifted toward more challenging low-frequency and long-wavelength regimes, where efficient electromagnetic energy (EM) dissipation is intrinsically

more difficult. Zhang et al. [171] developed a multifunctional carbon foam decorated with nanoscale chiral magnetic heterostructures, targeting low-frequency absorption by enhancing magnetic coupling. As shown in Fig. 13(c), the carbon foam combined magnetic functionality with structural robustness and achieved full C-band coverage (4 GHz bandwidth) together with a total EAB of 14 GHz (Fig. 13(d)), outperforming many previous reports. Additionally, Zuo et al. [172] used wet chemical and pyrolysis method to fabricated Co-anchored and N-doped carbon layers on the CNCs surfaces (Fig. 13(e)). The synergistic interaction between magnetic Co nanoparticles and the conductive helical

carbon network improved low-frequency impedance matching and strengthened magnetic-related losses (e.g., eddy-current-associated dissipation), yielding an $RL_{\min}$ of -35.6 dB at a thickness of 2.8 mm.

Recent efforts have also moved beyond intrinsic EM metrics toward multifunctional performance under realistic environments and scalable production. Ren et al. [173] synthesized super-helical PPy nanofibers via a soft-template route, where super-helical chirality enables cross-polarization while the dense polymer network serves as a protective barrier against corrosive media. At a low loading of 6 wt.%, the absorber achieved an EAB of 5.4 GHz and an $RL_{\min}$ of -44.5 dB, while providing $\sim 96\%$ corrosion protection efficiency. Furthermore, Li et al. [16] fabricated lightweight, resilient spring-like carbon nanofibers (SCNFs) via controlled chemical vapor deposition (Fig. 13(f)). The high curvature and defect-rich geometry enhance EM attenuation, while the elastic porous scaffold enables efficient oil/water separation, demonstrating a multifunctional route toward absorption-plus-remediation systems. The SCNFs achieved an $RL_{\min}$ of -50.4 dB with an EAB of 4.1 GHz at a thin thickness of 1.74 mm. From a manufacturability perspective, Sun et al. [174] grew helical carbon microcoils on low-cost carbonized toilet-paper substrates using CVD, forming continuous conductive helical networks on a fibrous skeleton and reducing reliance on expensive substrates. The resulting material delivered a broad EAB of 7.4 GHz at a 10% loading, offering a cost-effective pathway toward scalable absorber production.

5 Conclusions and future perspectives

In summary, helix-enabled advanced fibrous devices have emerged as a versatile platform for next-generation soft systems, bridging structural mechanics, materials engineering, and functional device design. By leveraging three-dimensional coiled geometries across 1D fibers, 2D membranes, and 3D assemblies, these architectures translate geometric advantages, such as large elastic deformability, hierarchical porosity, and amplified stimulus responses into broad device-level gains in sensing, actuation, energy harvesting/storage, environmental filtration/adsorption, and thermal/electromagnetic management. As research continues to push helix-enabled fibrous technologies toward higher performance and wider applicability, key opportunities and challenges will increasingly converge on sustainable material selection and processing, controllable and scalable manufacturing, quantitative structure-property design rules, reliable operation under real-world conditions, and coherent multifunctional integration. Addressing these challenges will accelerate the transition from laboratory prototypes to deployable systems, and ultimately unlock the full potential of helical geometries as a foundational design paradigm for advanced fibrous devices.

5.1 Sustainable design

Helical fiber-based devices, enabled by programmable three-dimensional coiled geometries, have expanded application boundaries in wearable electronics, environmental remediation, and personal thermal management. In particular, for 2D helical fibrous membranes used in air filtration and oil-water separation, helix-induced hierarchical pore networks and enlarged specific surface area can enhance particle capture and interfacial contact efficiency, offering a structural pathway to simultaneously improve filtration efficiency, dust-holding capacity, and pressure-drop management. Despite these advantages, most reported helical

fibrous filters and separation media are still predominantly constructed from non-renewable petrochemical polymers (e.g., TPU, PAN, PVDF, and PP). This reliance raises growing concerns regarding sustainability and life-cycle management, especially because filtration media are often consumed as disposable products in large-scale environmental applications. Without recyclability or degradability by design, widespread deployment may lead to solid-waste accumulation and long-term environmental persistence. Moreover, end-of-life treatment of highly stable polyolefins and certain fluorinated polymers may impose additional environmental burdens.

Future research should elevate sustainability from a materials-substitution problem to a life-cycle co-design strategy. First, renewable platforms such as cellulose-based materials (e.g., regenerated cellulose, CNF) and biodegradable aliphatic polyesters (e.g., PCL and PLA) should be explored, with systematic evaluation of their processability, helix-forming capability, and structural stability during and after fabrication. Second, greener processing routes are needed to minimize toxic-solvent use by adopting water-based/low-toxicity or recyclable solvent systems, while carefully assessing how post-treatments (e.g., crosslinking, curing, and encapsulation) may compromise degradability. Third, when introducing functionalities such as antimicrobial activity, electrical conductivity, or hydrophobicity, environmentally benign components and design-for-recovery strategies should be prioritized to avoid high-risk additives that hinder recycling or pose ecological concerns.

5.2 Structural control scalable production

Controlled helical geometry is a decisive factor in helix-enabled fibrous devices, governing not only mechanical compliance and fatigue behavior, but also pore architecture and mass-transfer resistance. Therefore, achieving precise control over helical parameters and batch-to-batch consistency across 1D fibers, 2D membranes, and 3D fluffy assemblies is essential for translating laboratory prototypes into scalable technologies.

For 2D/3D helical assemblies, controllable fabrication remains challenging, especially in electrospinning-based routes where composite jets evolve under coupled multi-physics effects, including electric-field-driven jet dynamics, solvent evaporation, aerodynamic perturbations, and jet instabilities. As a result, key descriptors such as pitch, helix diameter, and turn density are often difficult to regulate predictably. Future progress should move from empirical tuning to mechanism-driven programmable manufacturing, in which multi-physics numerical simulations/modeling are integrated with process optimization to enable more controllable helix formation and more reproducible structural “encoding”.

Scalable production is equally critical, particularly for environmental applications that require large-area, low-cost, and continuously supple materials. High-throughput platforms such as airflow-assisted spinning provide a practical foundation, coupling these processes with helix-formation principles may enable efficient construction of 2D/3D helical architectures at high yield. Nozzle arrays and roll-to-roll collection further offer viable routes toward scalable manufacturing.

5.3 Application prospects

Beyond advances in fabrication and structural design, the application prospects of bioinspired helical fibers are equally important. In flexible sensing, helical architectures offer a unique

route to simultaneously improve stretchability, structural compliance, and signal responsiveness. Their geometry-dominated deformation can effectively buffer external strain while amplifying resistance, capacitance, or triboelectric variations, making them highly promising for ultrasensitive wearable health monitoring. In addition, the fiber-like configuration of helical sensors is inherently compatible with textile integration, which provides a practical pathway toward breathable, conformable, and mechanically robust smart garments for long-term physiological monitoring. In filtration and separation, the value of helical fibers lies not only in material selection but also in their ability to reshape pore architecture. Helical geometries can introduce more open, interconnected, and hierarchical porous networks, which are beneficial for balancing capture efficiency, transport resistance, and structural stability. These advantages make bioinspired helical fibrous materials particularly attractive for practical applications such as indoor air purification, personal protective filtration, and efficient oil/water or liquid separation. Future efforts should therefore further promote the translation of helical structural design from laboratory demonstrations to application-oriented filtration and separation systems.

5.4 Multifunctional integration

Most helix-enabled fibrous devices to date remain predominantly single-functional (e.g., sensing, actuation, or energy output). While this showcases the structural advantages of helicity (mechanical compliance and signal amplification), it falls short of the system-level capabilities required for wearable and implantable applications. In practice, coordinated functions—such as sensing, power, interconnects, and signal transmission—are often needed, yet assembling multiple single-function components or stacking device arrays increases integration complexity and introduces additional failure-prone interfaces.

Moving forward, priority should be given to coherent multifunctional integration, where multiple functions are coupled within a single helical fiber or a single helical unit to reduce device count and interface density. Representative directions include self-sensing helical actuators (actuation integrated with feedback), self-powered sensing via integrated energy harvesting, and strain-insensitive helical interconnects.

Data availability

No data was used for the research described in the article.

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Declaration of competing interest

The authors declare no conflict of interest in this work.

Author contribution statement

T. N. Z.: Writing – review & editing, writing – original draft, visualization, resources, investigation, conceptualization. Y. L.: Writing-review & editing, Writing-original draft. X. M. Z.: Writing – original draft, visualization. Y. C. Z.: Supervision, resources, funding acquisition.

Informed consent

Not applicable.

Ethics statement

Not applicable.

Use of AI statement

None.

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