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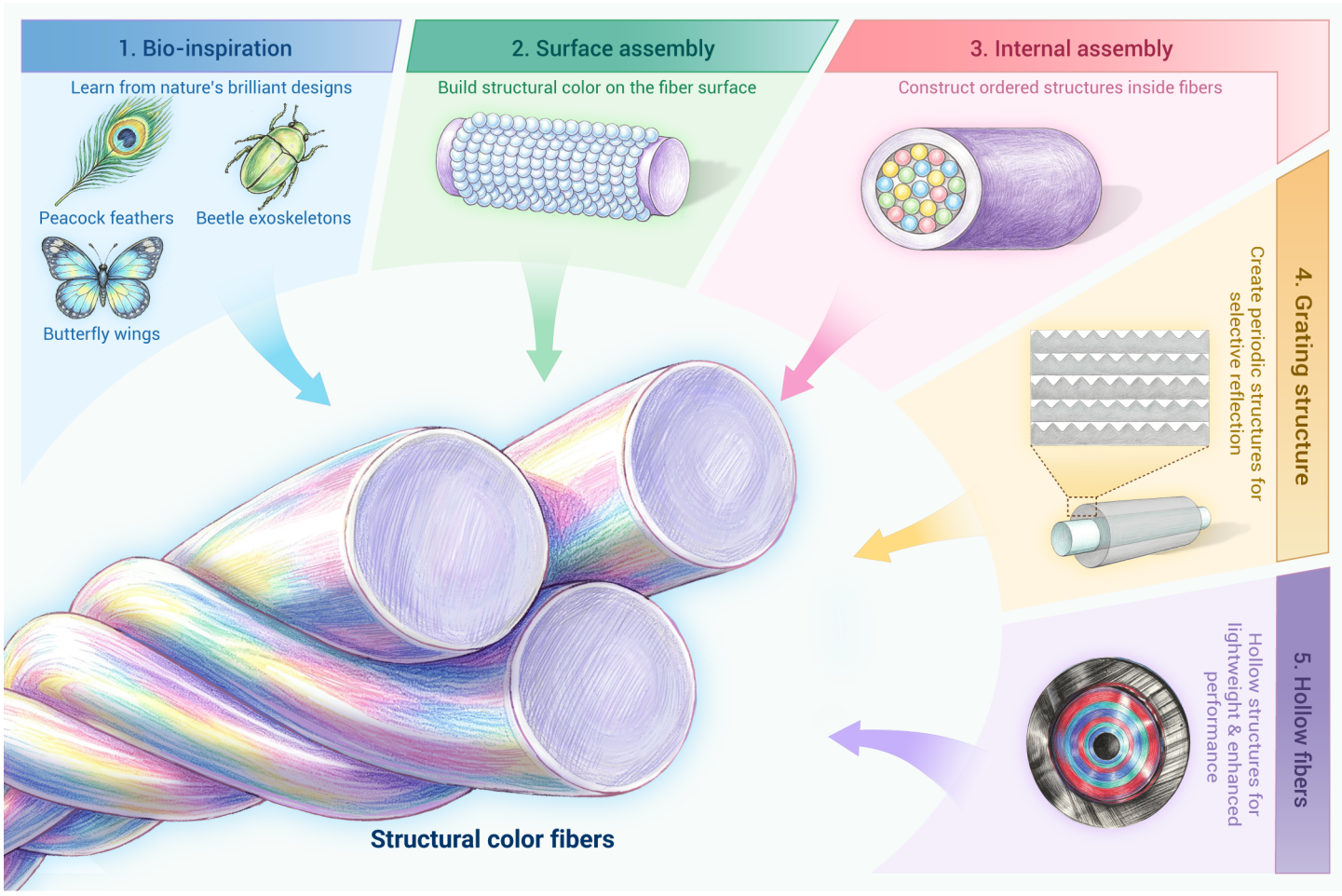
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Summary of fabrication technologies for bio-inspired structurally colored fibers.
- Understanding of upscaling nano/micro photonic structure into macro 1D configuration.
- Key challenges and future development prospects of structurally colored fibers.

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Architectural engineering of bio-inspired structural color fibers: From microscopic assembly to macroscopic fiber integration

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Bio-inspired structural color fibers (SCFs) with the combinations of the photonic effect of natural structure color and the configurational freedom of fiber materials, are a new type of fiber materials with dye/pigment-free optical property and newly-emerged functions, showcasing broad application prospects in smart textile, flexible optical display, and visual sensing. The key point for SCF fabrication is developing nano/micro-scaled structure into macro-scale one-dimensional (1D) configuration, while the high aspect ratio and curved surface of 1D configuration are prone to make the structure disordered. In this regard, considerable efforts have been made to overcome the issues. In this review, we give a fundamental and insightful study on the correlations between 1D photonic structure engineering and eventual SCF fabrication, started with introducing natural structure color principles. Next, we deeply study the fabrication techniques available for upscaling nano/micro photonic structure into macro 1D configuration. Finally, insights into the future challenges in the field of SCF materials, regarding the micro-scale photonic assembly balanced with the macro-scaled continuous fiber forming and the translation of structure color fibers technology from academia to industry, are proposed.

INTRODUCTION

Structure color widely exists in creatures, like the bright blue of the *Morpho Menelaus*,[1,2] the iridescence of the peacock's feathers,[3] the ever-changing pink crown of the *Calypte anna*'s head,[4] the metallic sheen of the beetle's shell,[5] and the brightly-colored fruit-*Pollia condensata*.[6] Differing from the chromophores-based chemical pigments and dyes, structure color based on light-matter interactions shows facilitating superiorities including high saturation, non-photobleaching, and environmental friendliness, very superior to the pigmentary coloration which commonly suffers photochemical degradation and has impact on the environment.[7] With outstanding features, nowadays, a bunch of artificial optical materials inspired by natural structure color have been widely developed by using building block nanomaterials with controlled variable nanostructures that can reproduce the biological structure itself.[8-13]

Structural color fibers (SCFs) are newly emerging bio-inspired photonic materials, with an amazing configuration composed by ordered nano/microstructure coupled with continuous cylindrical geometry with an infinitely extended axial-symmetrical space.[14] That is quite distinguished from the common photonic film materials with two-dimensional (2D) planar orientation of photonic architecture. With integration of the photonic effect of structure coloration and the mechanical flexibility and high degree of configurational freedom of fiber materials,[15] SCFs have gained considerable attention and are of special interest in the field of smart wearable optics. SCFs could give themselves vivid and tunable color that relies on introducing special structures such as periodic media layers, micro-nano pores, or cholesteric organization on their surfaces or inside their matrix,[16] *via* either bottom-up or top-down techniques. Specifically, as shown in Figure 1, SCFs make their academic debut in 2010, which are fabricated by using a capillary tube as a template to support solvent evaporation-induced colloidal assembly of silica microparticles within it, that forms colloidal particle fibers with structure color.[17] Since then, great progress on colloidal self-assembly of diverse photonic structures to develop SCFs has been made.[18,19] In the same period, Steiner et al. prepared mechanochromic SCFs by rolling a bilayer polymer film.[20] In 2015, electrostatic spinning method has been adopted to prepare SCFs.[21] Thereafter, techniques available for SCFs construction have been widely explored, encompassing atomic layer deposition (ALD), microfluidics, and introducing grating microstructures.[22-24] Till to 2020, liquid crystal elastomers combined with various processing techniques, such as wet spinning, three-dimensional (3D) direct writing, and extruding, demonstrated great promising for fabricating SCFs with improved opto-mechanical performance.[25-30] Very recently, a new strategy of water-transfer printing technique has been proposed to develop SCF materials.[31] Accompanied by the development of fabrication techniques, the functionalization of SCFs also has made great progress. They are synchronously integrated with multiple functions such as color rendering, sensing and energy conversion through structural design, as a result endowing intelligent characteristics like dynamic optical response and environmental interaction, meanwhile maintaining the inherent comfort and processability.[32-34] That would significantly expand the application of SCFs, evolving from fixed, simple optical displays to cutting-edge wearable flexible optical sensors.[35,36]

In this review, we firstly give a comprehensive overview of the structural design, fabrication strategies, and hence the construction of SCFs. We begin by briefly introducing the basic concepts of natural structure color and the associated different underlying mechanisms, to reveal the bioinspiration principles for SCFs. Then, we carefully discuss the interplays between different structural designs, techniques, and the eventual SCFs fabrication, based on different photonic effects of natural structure color. The key points affecting the formation of nano/micro-scaled ordered structure along with the macro-scaled fiber processing, hence the final structural color property within 1D fiber configuration, are carefully studied and discussed. Finally, we consider the future research directions and challenges regarding the modulation mechanism of the SCF architecture optimization, the upscaling of SCF fabrication, and the translation of SCF from academia to industry.

STRUCTURAL COLOR PRINCIPLES

The study of structural color mechanism can be traced back as far as 1665, Hooke and Newton first reported the iridescent color of peacock feathers.[37] In 1942, Anderson and Richards revealed that the structure color mechanism was highly related to microstructure.[38] It has been well understood that well-organized hierarchical micro/nanostructures are critical for the generation of structure color in nature.[39] Those structures featured with hierarchically organized periodic structures at multi-length scales, enable the controllable light-matter interactions to generate structure color.[40-42] Nowadays, natural structural color phenomena have been extensively investigated and encompass any colors resulted from the interaction between structure and light, mainly including interference, diffraction, and scattering of light. Inspired by those natural structural color principles, nowadays, researchers are developing a bunch of artificial SCF materials.

Light interference

When light traveling between two or more reflective surfaces, it undergoes constructive interference at specific wavelengths due to path length differences, while destructive interference occurs at other wavelengths leading to their attenuation. That could induce the generation of structure color. Such light interference associated with structure color can be divided into thin-film interference and multilayer interference (Figure 2A). A typical natural example for thin-film interference-induced structure color is the colorful soap bubble (Figure 2B).[43] The effects of thin-film interference are attributed to different refractive indexes of films, which are significantly influenced by the film thickness and the angle of incidence of light, with the interference pattern being

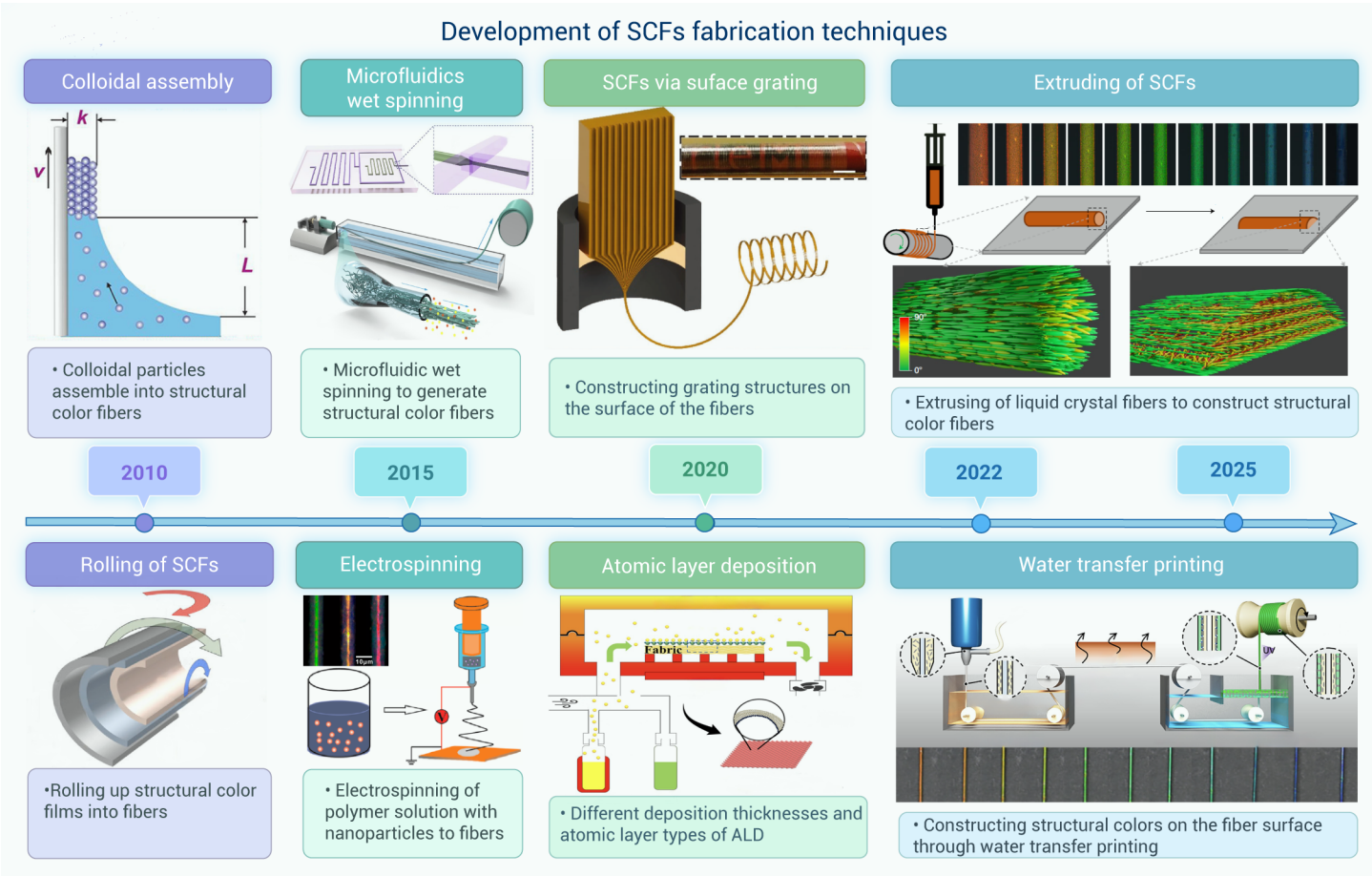


Figure 1. Timeline of the development of SCF fabrication techniques.

governed by the optical path difference. Compared to thin-film interference, structural colors produced by multilayer periodic structures exhibit more vibrant and highly saturated hues, which are widely distributed in nature. For example, the metallic sheen of beetle shells results from the multi-layer light interference due to the multilayer periodic structure existing in their cuticle.[44] Especially, the multilayer periodic structure undergoes a spatial chiral twist, forming a chiral helical (cholesteric) multilayer periodic structure.[45] Such structural organization additionally causes the polarization of light interference, thereby generating structural color with circular polarization.

Light diffraction

Periodic microstructures with spacing commensurate matched with light wavelengths can function as diffraction gratings. When the periodic structure of the grating is comparable to the wavelength of visible light, the structure produces an iridescence effect (Figure 2C). Specifically, when light incidents on the structure, the diffraction effect disperses light with different wavelengths into distinct spatial directions, thereby generating a continuous rainbow spectrum that shifts with the viewing angle. This diffraction grating structure is commonly found in invertebrates. For example, the wings of Blue *Morpho* butterfly exhibit multilayer periodic structure longitudinally coupled with a diffraction grating structure transversely. Such architecture accounts for the striking color of the wings (Figure 2D).[46–48] In plants, the rainbow colors of tulip petals also originated from the periodic diffraction grating structure in the surface cuticle layer.[49]

Light scattering

In addition to periodic structures, non-periodic structures can likewise produce structural colors. For example, some disordered porous structures and quasi-crystalline structures, are capable of producing structural color by coherent scattering effect (Figure 2E). The key point of coherent scattering is no longer the periodic structure, but the phase relationship of the scattered wave. Specifically, when the size of the scatterer is close to the wavelength of light and has short-range ordering, phase-length interference occurs between multiple levels of scattered light, as a result producing specific color. The typical natural examples involving light scattering-induced colors are blueberries (Figure 2F), which do not contain any blue pigments but present vivid blue optical appearance, due to the surface structures of blueberries consisting of randomly-arranged waxy crystals which function as non-spherical scatterers.[50]

Inspired by the above three kinds of light-matter interactions, the corresponding hierarchical micro/nanostructures associated with light interference, scattering, or diffraction, have been integrated with macro-scaled one-dimensional (1D) fiber geometry to develop a variety of SCFs. However, it faces great difficulty in combining micro/nano-scaled photonic structures with macro-scaled fiber configuration in an ordered manner. In this regard, structural engineering of SCFs involving introducing photonic structures onto fiber surface or within fiber matrix, or directly developing well-defined micro/nanostructures from fibers themselves, has been widely conducted. As a matter of fact, different combinations between micro/nano-scaled photonic structures and macro-scaled fiber geometry strongly affect the final performance of as-built SCFs. The following sections give a comprehensive summary on the design and construction of SCFs, from aspects of design principle, fabrication strategy, and structure regulation.

CONSTRUCTION OF STRUCTURAL COLORS ON FIBER SURFACE

Inspired by structure color in nature, the key point is applying building blocks nanomaterials with controlled variable nanostructures that can reproduce the biological structure itself.[51–53] Specifically, the structure coloration of fiber materials relies on ordered microstructure constructed along the curved surface of fiber. As compared to photonic architectures commonly generated in film form, controlling building blocks to orderly align along the fiber surface that forms photonic microstructure faces higher difficulty, due to the

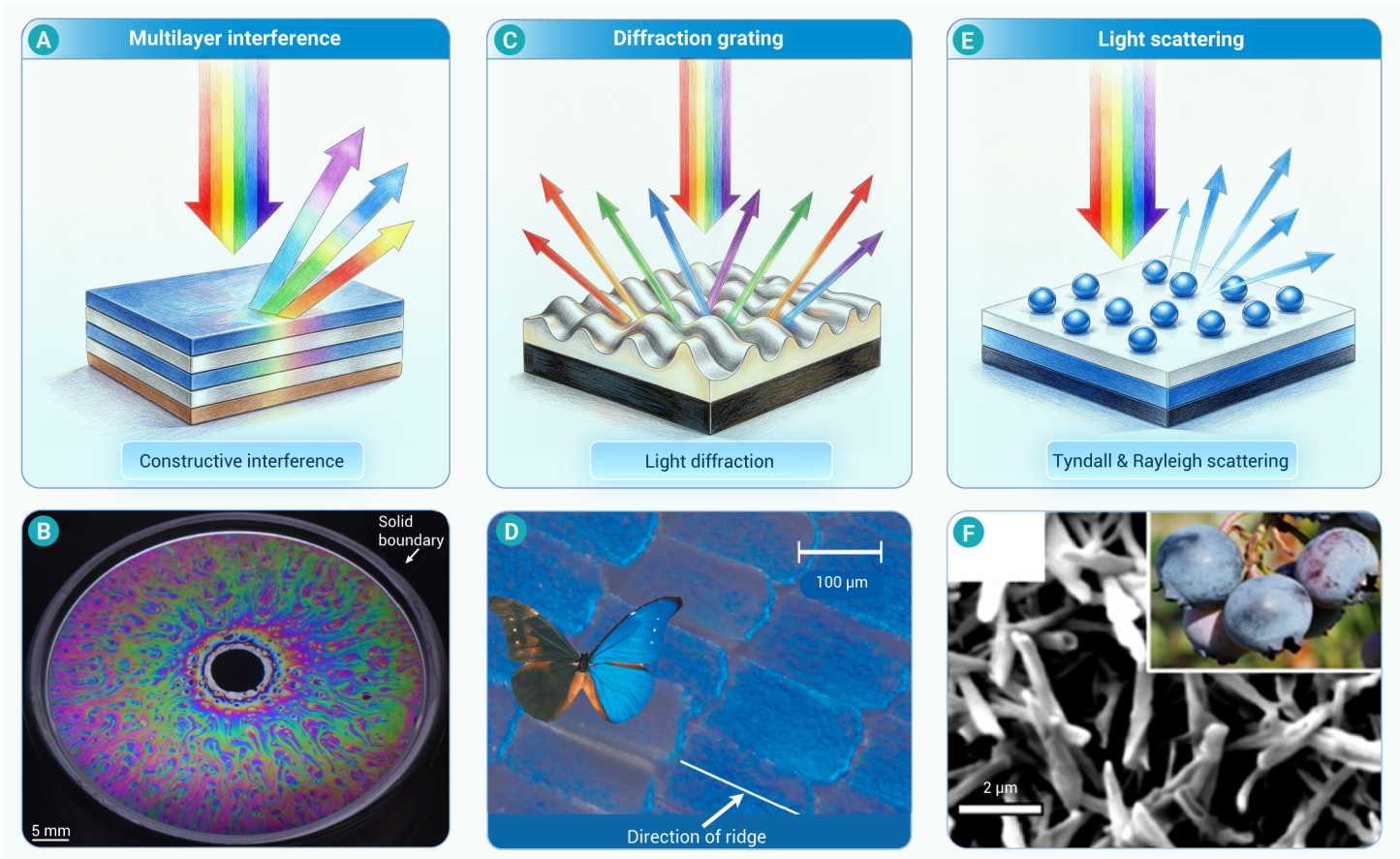


Figure 2. Structural color principles for the design of SCFs Schematic diagram of (A) multilayer film interference. (B) Thin-film interference color exhibited by soap bubble. Figures reproduced with permission.[43] Copyright 2023, AIP Publishing. (C) Schematic diagram of the effect of grating structure on light diffraction. (D) Great Blue Morpho butterfly and the grating structure on its wing surface. Figures reproduced with permission.[46] Copyright 2009, AIP Publishing. (E) Schematic diagram of light scattering by non-periodic structures. (F) Microstructure of wax bloom crystals on the surface of blueberries. Figure reproduced with permission.[50] Copyright 2024, AAAS.

high-aspect-ratio and curved topography prone to make the microstructure disordered. In addition, the requirement for good interfacial compatibility between fiber substrate and building blocks limits the universality of structure coloration to fiber materials. In this regard, researchers have made great efforts to address the two aforementioned challenges. Diverse strategies have been adopted to introduce sub-wavelength photonic structures, including thin-film and multi-layer interference layers, chiral nematic coatings, as well as disordered structure, onto fiber surface. In this part, we will discuss the construction, controlling, and fine tuning in those photonic structures on fiber surfaces.

Thin-film interference layer on fiber surface

Structural colors based on thin-film interference are common in nature. Thin-film interference highly depends on the refractive index and the thickness of each layer, both are quite essential to ensure a constructive interference of light produced by each layer, hence reflecting a particularly bright color. Based on this principle, carefully selecting building blocks to construct thin-film interference layers with well-controlled thickness onto fiber surfaces, has been well demonstrated to develop SCFs, and the techniques involve metal oxide coating with ALD and surface grafting of polymeric layer.

Metal oxides layer with ALD

Commonly, ALD involves two self-limited surface reactions to form binary compound films with atomic level control, showing merits of high efficiency, accurate and uncomplicated thickness control, and good conformability to various surfaces.[54] Especially, ALD technique enables the chemical growth of periodic nanostructures of metal oxides along the curved surface of carbonaceous fiber conformably.[55] The refractive index contrast between metal oxides, air, and fiber surface, collaborated with the precisely-controlled layer thickness, generate thin-film interference effect hence bringing brilliant structure color for common black carbonaceous fibers. Considering the chemical inertness of carbon surface, before ALD-based structural coloration, those carbonaceous fiber surfaces are activated by plasma treatment or grafted onto them highly active oxygen-containing functionalities. Those newly formed active sites then react with the precursor molecules to form chemical bonding. With the following ALD process, periodically photonic microstructure of 1D periodic layers composed by metal oxides is grown onto fiber surface with a strong interfacial interaction.

With ALD method, for example, Zhang's group[56] realized the structural coloration for carbon nanotube fibers (CNTFs) by growing thin amorphous layers of titanium dioxide (TiO_2) onto CNTF surfaces (Figures 3A-B). It has been demonstrated that the coating of TiO_2 produces synthetic effects of thin-film interference, refraction, and reflection to bring structural color (Figure 3C). By tuning the thickness of TiO_2 coating layer, CNTFs with multiple colors including blue, yellow, purple, and green are achievable (Figure 3D). Moreover, with TiO_2 coating that the resulting colorful CNTFs enable remarkable superdurability which could endure 2000 cycles of laundering tests, over 10-month-ultraviolet irradiation, and a notable fire-retardant performance. To further improve the hue, saturation, and brightness of structure color, Zhang's group coated bilayer metal oxide film onto CNTFs via ALD technique.[55] With adjusting the combinations of aluminum oxide (Al_2O_3), zinc oxide (ZnO), or TiO_2 and the thickness of each oxide layer, colorful CNTFs with wide color gamut and high saturation are obtained. Such structural coloration of CNTFs is a comprehensive result of thin-film interference and surface roughness. Moreover, as-resulted colorful CNTFs are non-iridescent due to the rough surface decreasing the color dependence on view angle, that benefits to expand the applications for colorful CNTFs.

Surface grafting of polymeric layer

The installing structural color on fiber especially carbon fiber possibly

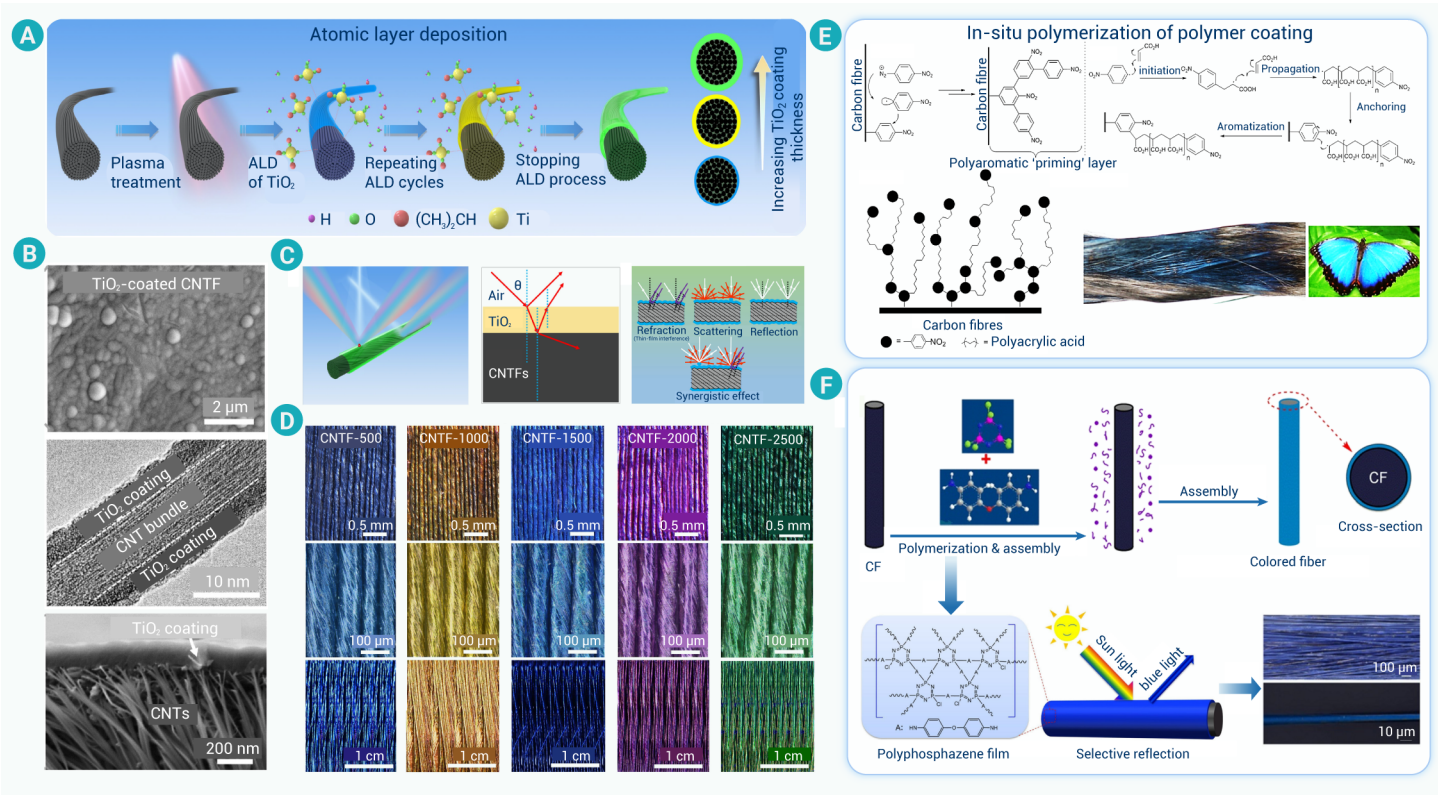


Figure 3. Construction of thin-film interference layer on fiber surface (A) Schematic illustration for preparing colorful carbon nanotube fibers by coating TiO_2 through ALD. (B) Morphology of TiO_2 coating on carbon nanotube fibers surface. (C) Synthetic effect of thin-film interference, refraction, and reflection resulting in structural color on carbon nanotube fibers. (D) Photographs of colorful TiO_2-coated carbon nanotube fibers. Figures reproduced with permission.[56] Copyright 2022, AAAS. (E) *In situ* surface modification with acrylate polymers on carbon fibers to prepare structural color carbon fibers, and the image of the surface-modified carbon fibers highlighting the blue color similar to the *Morpho* butterfly. Figure reproduced with permission.[57] Copyright 2019, ACS. (F) Schematic for the structural coloration of carbon fiber enabled by poly(cyclotriphosphazene-co-4,4'-oxydianiline) thin-film coating, and image of as-resulted colorful carbon fibers. Figures reproduced with permission.[58] Copyright 2024, Elsevier.

raises concerns regarding fiber strength and stiffness, interfacial adhesion within a polymeric support, and processability. In this regard, *in-situ* surface grafting a polymeric layer with thickness of hundreds of nanometers onto carbon fiber surface, that not only allow to generate thin-film interference coating stabilized by chemical bonding, but also improve the compatibility between carbon fiber and resin to extend the processability. However, the graft polymerization lacks controllability in polymer growth, thus usually forming localized areas of polymer coating with the variation in thicknesses on fiber surface and hence resulting in sporadic coloration. With surface grafting polymerization, for example, Eyckens et al.[57] introduced a polyacrylic acid film onto carbon fiber surface. The polymer coating layer generates thin-film interference effect that imbues the fibers with an electric blue color (Figure 3E). Meanwhile, with modifying the fiber surface by polyacrylic acid, the resulting fibers show significantly increased tensile strength as well as great interfacial adhesion with epoxy. As a result, the fibers can be reversibly formed into complex shapes and bear significant loads without obvious structural damage. Additionally, a layer of poly(cyclotriphosphazene-co-4,4'-oxydianiline) film has been polymerized on carbon fiber surface to generate thin film interference hence bringing vivid colors (Figure 3F).[58] The good thermo-oxygen stability of N-P heterocycles and the cross-linked networks formed in coloration coating, endow fiber excellent thermal durability against 300°C-heating treatment. Moreover, due to the surface chemical activity of polymer coating, the colored carbon fiber shows enhanced tensile strength and exhibits great compatibility to resin with strong interfacial adhesion.

Multilayer interference coating on fiber surface

In nature, multi-layer interference is usually associated with photonic crystals, which are organized optical structures with periodic modulation of the refractive index at the sub-micron scale capable to control light propagation.[59] Once the photonic gap is within the visible wavelength range, the highly organized structures can generate intense structural colors. Photonic crystals are divided into one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D), corresponding to the structural periodicity in one, two, and all three directions, respectively. Typical 1D photonic crystals in nature are the stacks of thin crystalline nacreous platelets under the shells of the mollusks.[60] The well-known creatures having 2D photonic crystals are the transparent cicada wing and the moth eye.[61,62] The most famous 3D photonic crystals are the periodic systems with densely packed spheres in natural opals. With well understanding the self-organized systems of those creatures in nature, periodic nanostructures have been installed onto fiber surface to create SCF materials, via dip coating-assisted colloidal assembly,[63] external field-assisted photonic assembly, or cholesteric liquid crystal (CLC) coating.

Dip coating-assisted colloidal assembly

Colloidal self-assembly *via* dip coating is a simple and effective technique to create photonic crystal structure along fiber surfaces. This technique allows the control of the homogeneous growth of particle arrays at the substrate-air-solution interface. In this process, the fiber is vertically immersed into the colloidal suspension with the presence of adhesive polymer, and then it pulls out from the colloidal suspension. With drawing and evaporation that induces an upward convective flow to carry the particles into the meniscus tip. The lateral capillary force between the particles then connects them to each other, and finally form a close-packed particle array along the fiber surface with a strong interface stabilized by a polymer interpenetrated network. The success of dip coating technique depends critically on the balance between withdrawal speed and evaporation rate, which dominates the thickness and ordering of as-packed photonic layer. Moreover, with appropriately adjusting the fiber substrate, colloidal concentration, particle size, and drawing speed, the photonic coatings on the fibers can be readily controlled as desired.

With dip coating, Yuan et al.[64] directly drew a bare hydrophilic polyethylene terephthalate fiber out from the colloidal suspension of poly[styrene-*co*-(butyl acrylate)-*co*-(acrylic acid)] (P(St-BA-AA)) polymer spheres (Figure 4A). During

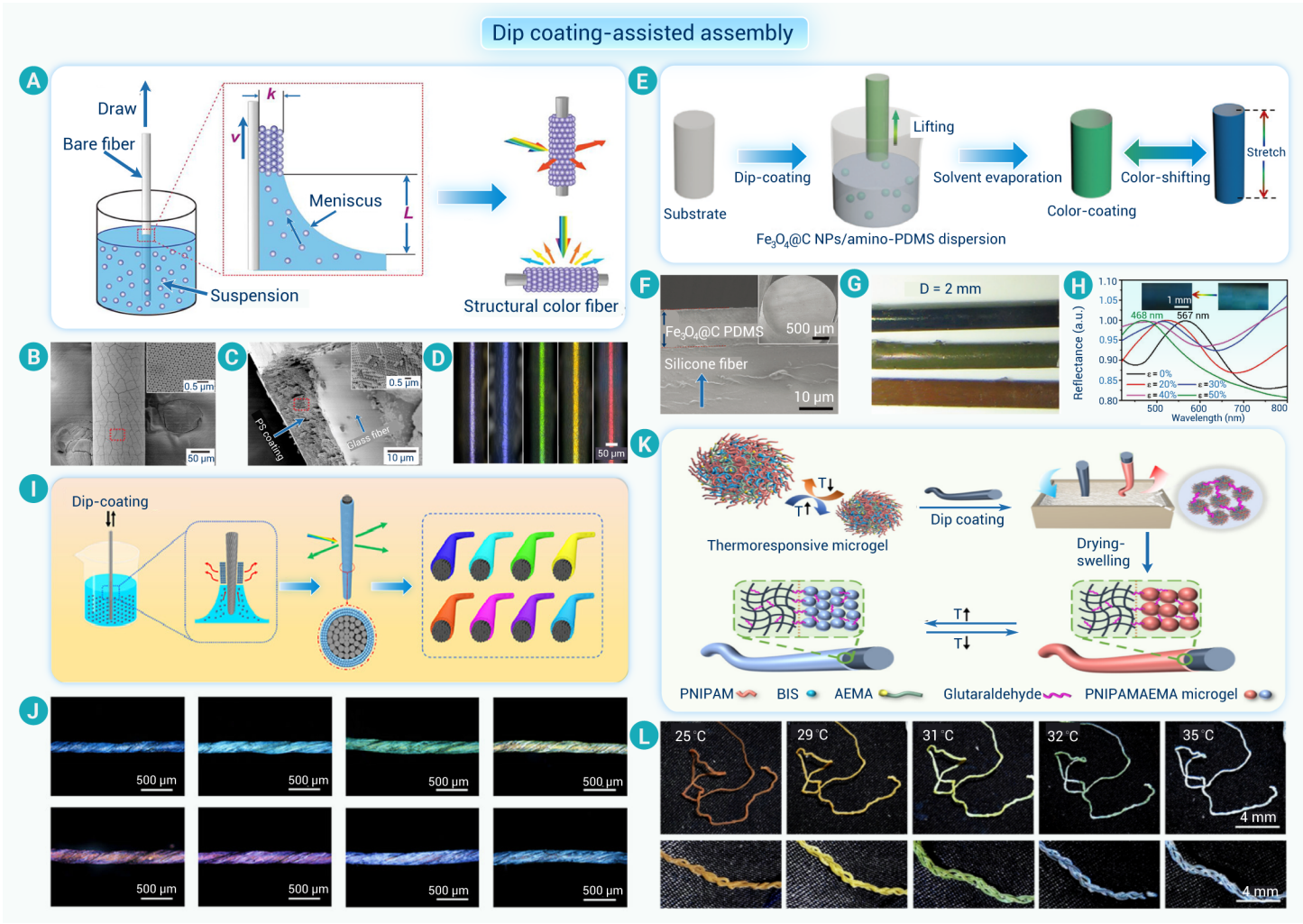


Figure 4. Construction of multilayer interference coating on fiber surface (A) Schematic illustration for the fabrication of SCF by directly drawing bare fiber from colloid suspension of poly[styrene-*co*-(butyl acrylate)-*co*-(acrylic acid)] (P(St-BA-AA)). (B) Surface and (C) cross-sectional SEM images of the resulting SCF. (D) Images of prepared SCFs with different colors observed in a dark-field microscope. Figures reproduced with permission.[64] Copyright 2019, ACS. (E) Mechanochromic SCFs with Fe_3O_4@C/PDMS polyethylene coating. (F) Cross-sectional SEM image of the mechanochromic SCFs. (G) Mechanochromic SCFs with different colors. (H) Reflection spectra of mechanochromic SCFs at various strains ranging from 0% to 50%. Figures reproduced with permission.[65] Copyright 2020, Wiley. (I) Schematic representation of colorful CNTFs via dip coating SiO_2 nanospheres, and (J) photos of as-resulted colorful CNTFs with multiple colors. Figures reproduced with permission.[66] Copyright 2023, ACS. (K) Preparation of structural color hydrogel fibers and (L) their thermoresponsive performance. Figures reproduced with permission.[67] Copyright 2024, ACS.

pulling out the fiber and with solvent evaporation, particles are carried into the meniscus tip and finally forms a close-packed particle array on fiber surface with to gain vivid SCFs (Figures 4B-C). The optical properties of as-obtained SCFs could be flexibly adjusted via the tuning of drawing speed, the concentration of the colloidal suspension, and the diameter of the bare fibers, hence allowing color modulation from purple to red (Figure 4D). Additionally, dip coating of a transparent silicone fiber in precursor suspension containing carbon-coated Fe_3O_4 nanoparticles (Fe_3O_4@C NPs) and amino-polydimethylsiloxane (PDMS), followed by pulling out with low rate of 20 mm min^{-1},[65] that enables Fe_3O_4@C nanoparticles coated on the curved surface to produce structure color (Figures 4E-F). By tuning the diameters of Fe_3O_4@C nanoparticles from 126, to 164, and 195 nm, correspondingly, three SCFs with the colors of blue, green, and red are obtained (Figure 4G). Besides, the resulting SCFs show sensitive color response to mechanical force, with obvious blue shift in color with strain extended (Figure 4H). In addition, Zhang's group[66] realized the scalable production of colorful CNTFs via dip coating strategy (Figure 4I). Specifically, CNTFs were drawn out from SiO_2/ethanol dispersion in the presence of poly[(butyl acrylate)-*co*-(methyl methacrylate)] as an adhesive copolymer. With the rapid volatilization of ethanol, a uniform SiO_2 nanosphere layer is coated onto CNTF surface through a convective self-assembly mechanism to generate brilliant colors. The colors of SiO_2 nanoparticle-coated CNTFs could be easily changed by tuning the sizes of SiO_2 nanospheres (Figure 4J). Beyond the structure color fibers mentioned above, differently, Zhu et al.[67] developed hydrogel fibers with a dynamic structural color by using soft and thermal responsive microgels as photonic blocks with dip coating strategy (Figure 4K). In this way, a full interpenetrated sodium alginate-polyacrylamide hydrogel fiber is coated by poly(N-Isopropylacrylamide) (PNIPAM) microgels, which are assembled into close-contacted arrays on fiber surface to generate brilliant colors (Figure 4K). Due to the thermally responsive feature, the shrinkage in the distance between neighboring microgels occurs under temperature stimuli, that endows thermochromic properties for the resulting SCFs (Figure 4L). This versatile tunable structural color coating approach shows great potential for smart fibers.

External field-assisted photonic assembly

Despite dip coating allowing self-assembly of close-packed arrays onto fiber surface for structure coloration, such methodology usually takes long times, having the trade-off between great ordering and high efficiency. With this context, colloidal self-assembly with assistance of external forces, including thermal field, vacuum-induced process field, electrical field, and magnetic field, has been proposed and achieved great progress.[68] As comparison to common self-assembly, the presence of external force fields override the random thermal motion of building blocks and force them into ordered configurations even on curved fiber surfaces, demonstrating an efficient technique for SCF fabrication. For example, Liu et al.[18] developed a macroscale patterned SCF *via* an isothermal heating evaporation-induced

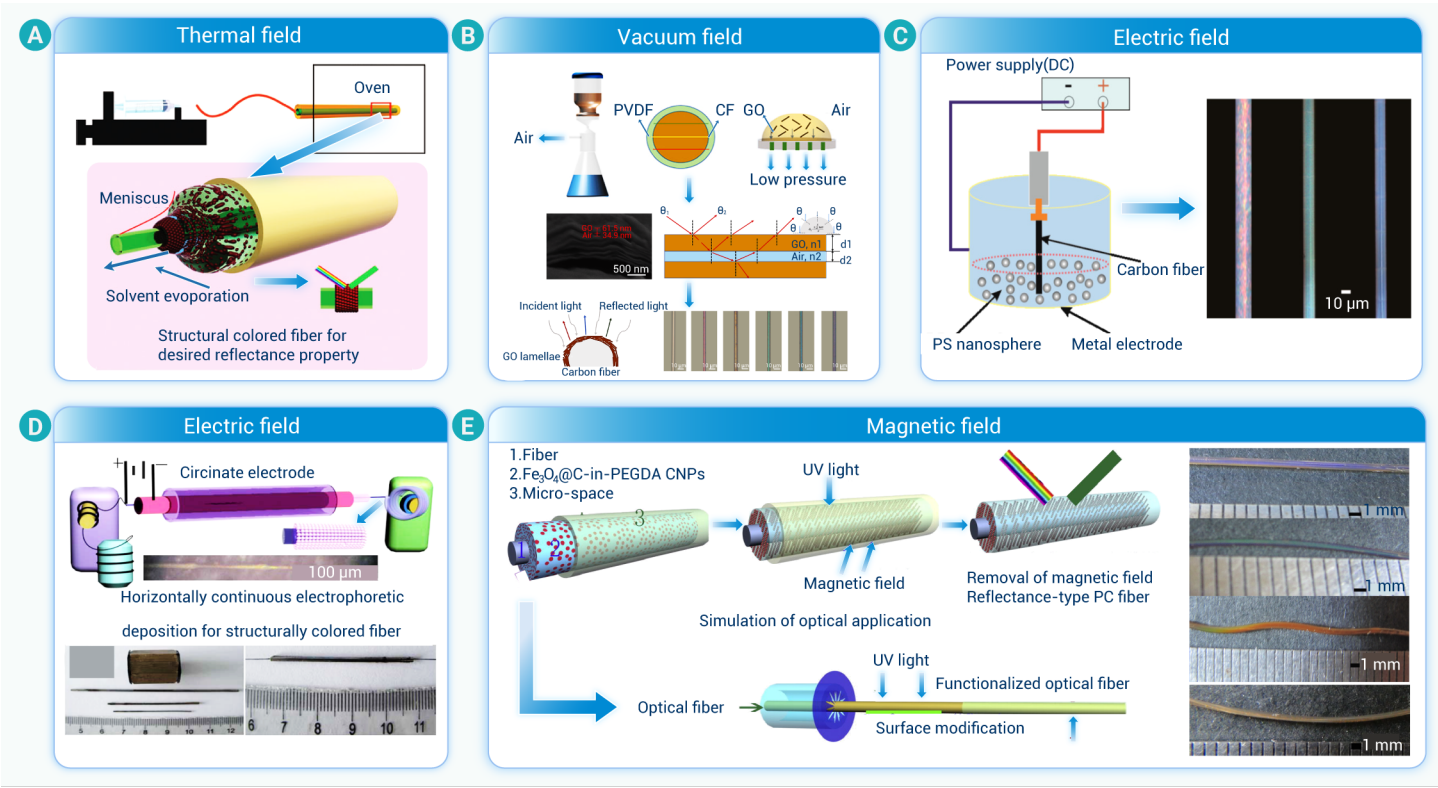


Figure 5. External field-assisted photonic assembly on fiber surface (A) Schematic diagram of the fabrication of isothermal heating evaporation-induced self-assembly opal structure onto a fiber in micro-space. Figure reproduced with permission.[18] Copyright 2011, RSC. (B) Fabrication of structural color carbon fibers by vacuum filtration and their coloring mechanism. Figures reproduced with permission.[69] Copyright 2022, Elsevier. (C) Schematic diagram of SCFs fabrication by colloidal electrophoretic deposition method. Figure reproduced with permission.[71] Copyright 2013, ACS. (D) Schematic representation of SCFs fabricated by electrophoretic deposition method under cyclic electric field. Figure reproduced with permission.[72] Copyright 2013, RSC. (E) Schematic diagram of magnetic field-induced preparation of SCF. Figure reproduced with permission.[73] Copyright 2013, Elsevier.

self-assembly method, *i.e.,* conducting colloidal self-assembly of silica colloidal spheres on fiber surfaces within microchannels with heating (Figure 5A). This method allows forming well-defined photonic bandgap fibers with lattice parameters tailored in a fast way, while it is difficult to operate. More feasibly, due to vacuum-induced pressure difference with capability to facilitate nanoparticles packed closely layer by layer, that provides a simple and facile way to construct highly ordered structure onto fiber surface. For example, Xu et al.[69] proposed that, with vacuum-induced pressure, 2D graphene oxides orderly stack together and self-assemble into a lamellar stacked structure on carbon fiber surface with great interfacial interaction (Figure 5B). As-stacked lamellar structure analogous to 1D photonic crystals as observed in nature, capable to generate photonic effect to bring structure color for carbon fibers.

Additionally, considering the significant charge feature of colloidal particles, electrophoretic deposition has been applied to construct an ordered photonic structure on a curving fiber surface.[70] For example, Zhou et al.[71] applied external electric field to assist the directional assembly of colloidal particles on the fiber surface (Figure 5C). Polystyrene colloidal spheres with different particle size were electrophoretically deposited onto carbon fibers to form cylindrical colloidal crystals, that yields core-shell colloidal fibers with multiple structural colors (Figure 5C). Liu et al.[72] also fabricated SCFs *via* electrophoretic deposition-induced assembly of charged poly(methyl methacrylate) microspheres on the surface of the electroconductive carbon fiber under a circinate electric field. They further extended such strategy to a horizontal and continuous process, hence allowing to fabricate long range SCFs with a higher efficiency superior to the gravity sedimentation technique which usually needs weeks or even months (Figure 5D). Moreover, in view of that magnetic field can trigger superparamagnetic colloidal nanoparticles to align into tunable structures very simply and efficiently, colloidal self-assembly under magnetic field has been applied to fabricate vivid SCFs by using superparamagnetic colloidal nanoparticles as building blocks. For example, Liu et al.[73] synthesized a photonic crystal SCF with fixed structure colors of blue, green, and red, by assembling superparamagnetic Fe_3O_4@C colloidal nanospheres with different sizes into chains on a flexible fiber under a magnetic field (Figure 5E).

Cholesteric liquid crystal (CLC) coating

CLC is a major class of photonic materials capable to self-organize into long-range ordered helical nanostructure.[74] CLC, at molecular scale, usually presents rod-like molecules locally self-assemble along a common direction called the director, **n**, further at micron scale, **n** rotates in a helical fashion along an axis **m** perpendicular to **n**. Once the helix pitch is on the scale of visible light wavelengths, CLC can function as 1D photonic crystal to reflect visible light hence producing structure color. Based on this, assembling well-ordered helical CLCs onto fibers holds promise to develop SCFs. However, the difficulty lies in the consistent formation and distribution of periodically radial helix structures along microscale curved geometries of fiber, which determines the angle-independent coloration and uniform structural color of SCFs. Once the alignment of the helix structure is tilted around the fiber, that would result in nonuniform and pale color. Keeping those in mind, the techniques including drawing coating, cladding coating, and water transfer printing (WTP), have been developed to introduce CLC layer onto passive fiber surfaces to construct coaxial structures, which will be discussed below.

For example, Guan et al.[75] cladded CLC coating around the surface of a black nylon filament, via pulling the bare fiber through a cylinder in which the CLC is fed (Figure 6A). Then the CLC clad fiber was drawn through an aqueous solution of polyvinylpyrrolidone (PVP) which is immiscible with CLC. With the solvent evaporating, PVP external sheath forms to support the CLC coating on fiber surface. That results in cholesteric fibers comprised of nylon fiber clad by a CLC mixture and stabilized by an outer PVP sheath (Figures 6B-C), which are capable to show dynamic color response to different external stimulus such as temperature variation (Figure 6D). With a similar drawing coating strategy, Zheng et al.[76] successfully developed active dual-stimulus-responsive cholesteric fibers, which show color change response to UV and volatile organic compounds stimuli. Those as-prepared cholesteric fibers

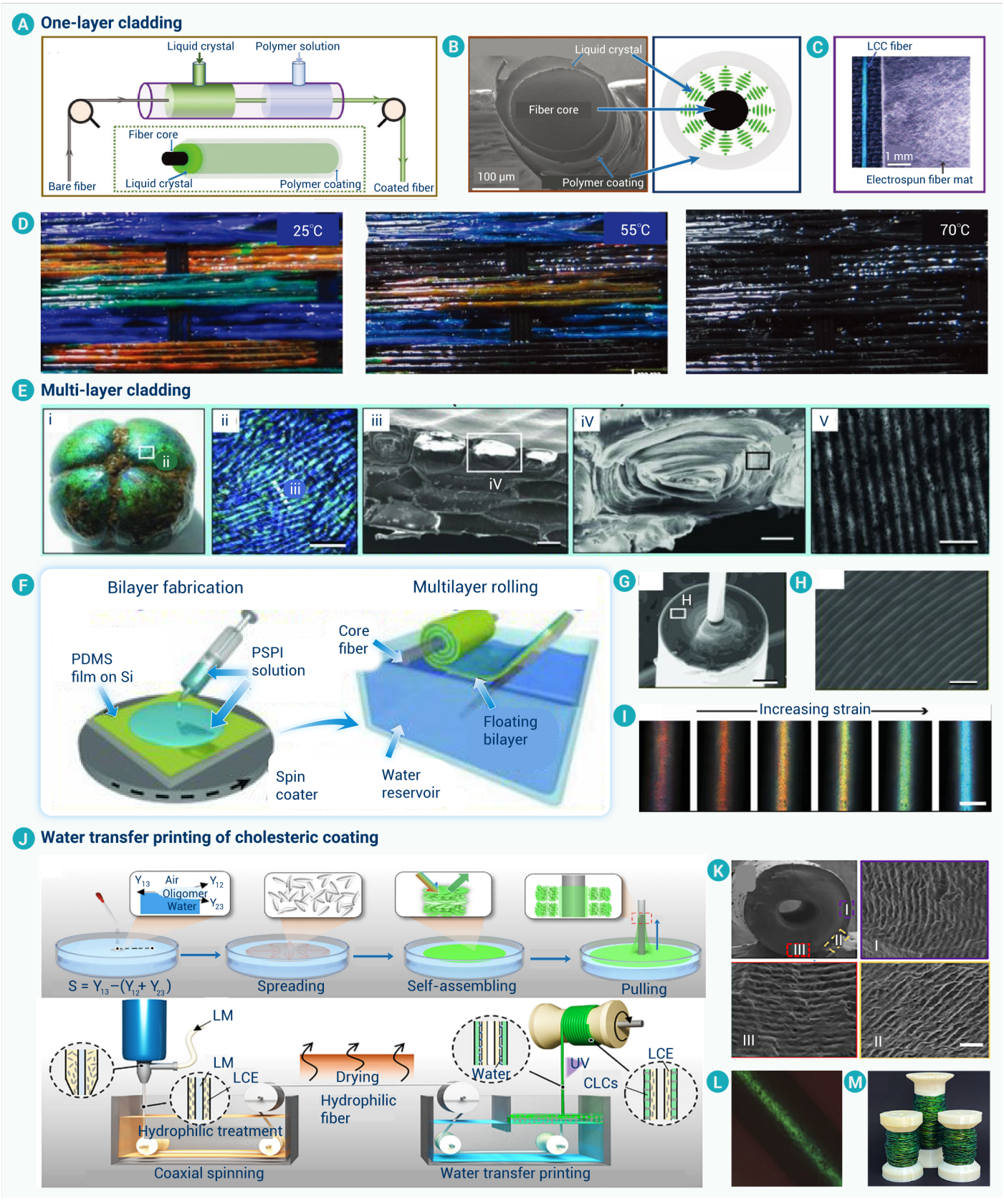


Figure 6. Cholesteric liquid crystal (CLC) coating on fiber surface (A) Schematic illustration of the preparation of SCFs with a single-layer cholesteric cladding. (B) Cross-sectional SEM image of the fiber. (C) Photo of the resulting SCF. (D) Color optical response of the fiber at different temperatures. Figures reproduced with permission.[75] Copyright 2019, Wiley. (E) Photonic structure in the seed coat of *Margaritaria nobilis* fruits. Scale bars: 200 μm (ii), 20 μm (iii), 10 μm (iv), 500 nm (v). (F) Schematic representation of the manufacturing of artificial photonic fibers with multi-layer cholesteric cladding. (G) SEM image of the fiber cross-section showing the multilayer cladding wrapped around the glass fiber core. Scale bars: 20 μm. (H) SEM image of the individual layers in the cladding. Scale bars: 1 μm. (I) The fiber showing color change response to mechanical strain. Scale bar: 50 μm. Figures reproduced with permission.[77] Copyright 2013, Wiley. (J) Schematic illustration of the WTP process and schematic fabrication of multi-functional SCFs by integrating WTP with coaxial extrusion. (K) Cross-section and helical pitch of the resulting multi-functional SCFs. The scale bar is 0.5 μm. (L-M) Photograph of mass production of multi-functional SCFs. Figures reproduced with permission.[31] Copyright 2025, Wiley.

were further woven into smart fabric, which can be used for monitoring the health status as well as the surrounding environment of wearers. That opens up new possibilities for personalized and responsive technology. Despite drawing technique enabling CLC coating onto fiber surface, the strong shear forces produced in drawing process inevitably induce a tilted alignment of the helix structure of CLC around the fiber, that hinders the formation of uniform radially helical orientation hence affecting the structure color saturation.

Inspired by the hierarchical photonic structure discovered in the seed coat of *Margaritaria nobilis* fruits,[77] in which several layers of cells are stacked on top of each other and the entire interior volume of single cell is occupied by a periodic concentrically layered morphology (Figure 6E),[77] cladding coating technique is proposed to develop SCFs. Firstly, a bilayer of two elastomeric dielectrics, *i.e.,* polydimethylsiloxane and polyisoprene-polystyrene triblock copolymer, was prepared, which is subsequently rolled up onto a thin glass fiber to form the multilayer cladding (Figures 6F-H). Due to the multilayer periodicity, the resulting fibers show a pronounced reflection in a finite wavelength range. Moreover, the resulting fibers present color change response to mechanical force. With stretching the fiber that the elongation along the fiber axis leads to a compression pressure to the fiber (Figure 6I), thereby causing a decrease of the overall diameter as well as a reduction in the thickness of each individual layer. That induces blue shift in color for the cladded SCFs.

WTP technique offers a significant opportunity to adapt interfacial nanoarchitectonics for the precise assembly of CLCs, thereby bridging the macroscopic conformality and the microscopic functional assembly required for photonic fibers. Very impressively, Chen et al.[31] applied WTP to implant CLC coating on fibers to realize structural coloration (Figure 6J). Firstly, the spreading and self-assembling dynamics of CLC oligomers are well controlled at the air-water interface. Thereafter, CLC oligomers are precisely transferred onto fiber surfaces followed by self-assembly to form radially aligned helical nanostructures. Moreover, integrating WTP with coaxial extrusion, scalable and continuous fabrication of highly saturated SCFs is realized. With this method, a multi-functional SCF with combinations of responsive structural color, robust actuation, and sensing is achieved, which is comprised by a radially aligned CLC photonic sheath, a uniform liquid crystal elastomer middle layer, and a conductive liquid metal core (Figures 6K-M). The proposed WTP-based approach demonstrates high-throughput fabrication of responsive SCFs for wearable devices.

Mie scattering structure on fiber

Apart from ordered alignment on fiber surface endowing structural coloration, it has been demonstrated that colloidal nanoparticles dispersed around fiber surface disorderly could generate Mie-scattering effect to bring structure color. For example, Xu's group[78] reported that the hydrothermal carbonization of glucose in the presence of carbon fibers could introduce carbon spheres attached and disorderly distributed onto the carbon fibers. Those disordered spheres share a high similarity to the structure of the peacock back feathers, which could generate Mie-scattering effect coupled with the single-particle resonance, as a result realizing the highly saturated colors in the disordered system. Besides, with adjusting the glucose concentration to tune the Mie-scattering effect, carbon fibers with multiple colors ranging from blue to green are achievable.

CONSTRUCTION OF STRUCTURAL COLOR WITHIN FIBERS

As discussed SCFs above are fabricated by assembling diverse nano/microstructures associated with structure color on fiber surface. In those cases, the interface between as-constructed structures and the fiber matrix is commonly stabilized *via* either chemical or physical effects. Nonetheless, those photonic structures are still prone to crack under severe mechanical force. As a contrast, directly developing photonic structure into macroscopic fiber is an alternative and efficient strategy to produce SCFs with great structural integrity and enriched functions. To achieve this, the assembly of building blocks should participate in the forming of fibers, during which the key point is to well control the confined assembly within closed high-aspect-ratio 1D configuration. Another concern is that the fiber forming process should have no influence on the as-assembled structure to generate structure color. Moreover, the Plateau-Rayleigh instability which is prone to break up precursor solutions into droplets also should be considered. Keeping those factors in mind, SCFs with different-type photonic assembles within fiber geometry, including chain-like structure, well-packed photonic array, CLC alignment, and chiral nematic organization, have been developed *via* diverse fabrication methods, such as microinjection, wet spinning, and electrospinning, which will be discussed in this part.

Chain-like photonic structure within fiber

Given that photonic structures commonly built by colloidal particles are not self-supporting, a polymer matrix is introduced to compatible with colloidal particles and then subjected to microinjection. The microfluidic injection confines the colloidal assembly within a tubular channel which acts as a mold to support fiber forming. Then, external fields are applied along the cylindrical geometry of the tubular channel to guide the ordering structure assembled. With this methodology, Li's group[79] had developed a series of SCFs by embedding superparamagnetic nanoparticles (Fe_3O_4@C nanoparticles) in polymer matrix via microfluidic injection method, during which magnetic field was applied to trigger those superparamagnetic nanoparticles to self-assemble into chain-like photonic structure within polyacrylamide fiber matrix. This structure selectively reflects visible light hence brings vivid color for the fiber. In addition, the distance between adjacent particles within chain-like assembled structures changes along with mechanical strain of the fiber, presenting mechanochromic feature. Using the same microfluidic injection system, another SCF with magnetochromic feature has also been developed by embedding the droplets of ethylene glycol (EG)-encapsulated Fe_3O_4@C nanoparticles into PDMS fiber matrix.[80] With external magnetic field, those Fe_3O_4@C nanoparticles within EG droplets experience reversible transition from isotropic to chain-like structures along the magnetic field. That induces the color of the fiber change from initial brown to yellow-green color. Differing from the above Fe_3O_4@C/polyacrylamide fibers showing color response to mechanical strain, the EG-coated Fe_3O_4@C/PDMS fibers always keep yellow-green color under a fixed magnetic field no matter they are stretched or squeezed. It is due to that the mechanical force only induced the morphology change of the droplets, while the distance between each adjacent Fe_3O_4@C spheres keeps the same. Moreover, since the alignment ordering of Fe_3O_4@C nanoparticles is packaged by PDMS matrix, the color of Fe_3O_4@C/PDMS fibers is stable and independent of environmental variations. Furthermore, to develop SCFs with environmental-adaptive dynamic colors, by embedding the chain-like assembly of Fe_3O_4@C nanoparticles into thermal-sensitive PNIPAM matrix under magnetic field, a thermochromic photonic fiber with bright and tunable structure colors could be obtained (Figures 7A-B).[81] Unlike Fe_3O_4@C/PDMS fibers having static color mentioned above, due to the lower critical solution temperature (LCST) of PNIPAM, as-prepared Fe_3O_4@C/PNIPAM fiber shows red and blue shift in color when immersed in water at a temperature below and above LCST, respectively (Figure 7C). That is attributed to that, at a temperature below or above LCST, the corresponding swelling and shrinking of the fibers occur, which accordingly induce the expansion and compression in the distance between Fe_3O_4@C nanoparticles. However, Fe_3O_4@C/PNIPAM fibers show dark color at dried state. It might be attributed to that the serious shrinkage of PNIPAM matrix with water removal induces decrease in the lattice spacing, which thereby leads a blue shift of the reflection peak wavelength out of the visible light range.

Well-packed colloidal array within fiber

Except the homogeneous chain-like structure, another ordered non-close-packed colloidal array is introduced into hydrogel microfibers to enable heterogeneous structural color by using a programmed injection microfluidic spinning technology.[82] Specifically, bioactive methacrylated gelatin (GelMA) pre-gel and silica nanoparticles array containing acrylamide (AAm), are alternately injected into a collecting tube. With the following UV curing treatment that heterogeneous structural color hydrogel microfibers can be obtained (Figure 7D). Within the resulting fibers, the segment components can be tuned via adjusting the injection procedures or adding the injection channels, that allows gaining different fibers with arbitrary bicolor and multicolor heterogeneous structures (Figure 7E). The adjacent two segments of non-close packed silica arrays and GelMA hydrogel are responsible for the vivid structural color and the great biocompatibility for cells adhesion and growth,

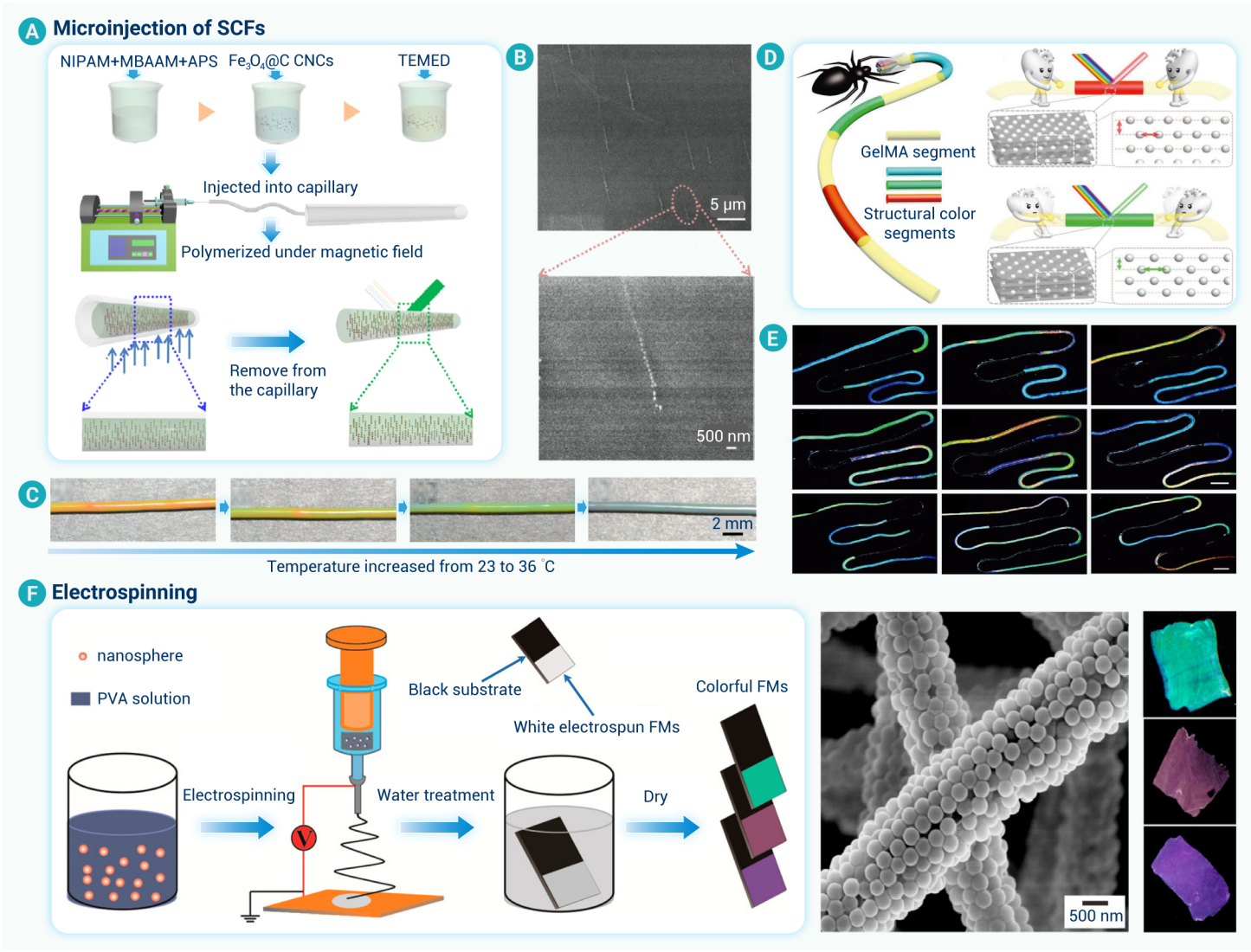


Figure 7. Photonic structure assembly within fiber (A) Schematic illustration of the preparation of the thermoresponsive SCFs and (B) cross-sectional images of the fibers. (C) Photographs of the thermoresponsive SCFs showing the color change when the temperature changes from 23 to 36°C. Figures reproduced with permission.[81] Copyright 2020, ACS. (D) Scheme of the programmed injection microfluidic spinning method for the fabrication of heterogeneous structural color hydrogel microfiber. (E) Optical images of six dichromatic heterogeneous microfibers in the combination of two orange, green, and blue segments (top and middle) and optical images of trichromatic heterogeneous microfibers with different color coding (bottom). Scale bars: 1 mm. Figures reproduced with permission.[82] Copyright 2021, Wiley. (F) Schematic diagrams of colloidal electrospinning to fabricate SCFs and their SEM images. Figure reproduced with permission.[21] Copyright 2015, ACS.

respectively. Based on this, as-resulted heterogeneous structural color hydrogel microfibers can act as a tug-of-war rope for cardiomyocytes, which provides a new horizon of heart-on-a-chip for biomedical applications.

Electrospinning strategy is another technique to allow the colloidal array formation within fiber to produce structure color. Electrospinning is usually producing fibers on nano-to-micron scale, which are interwoven with each other to form non-woven film.[83] Based on the technique, electrospun nano/micron SCF materials have been developed.[84] For example, Yuan *et al.*[21] massively produced uniform colloidal fibers via colloidal electrospinning method. Specifically, a blend solution of poly-(styrene-methyl methacrylate-acrylic acid) (P(St-MMA-AA)) composite colloidal spheres and poly(vinyl alcohol) (PVA) solution was subjected to colloidal electrospinning (Figure 7F). Within the mixture, a thin layer of PVA was wrapped on P(St-MMA-AA) spheres, and as-formed PVA soft shell acts as a binder to provide the adhesive force between colloidal spheres. During the electrospinning, the colloidal spheres were cylindrically packed with a local hexagonal order and thinned into the soft fibers. Those colloidal fibers can present non-iridescent structure colors with the following water treatment, during which a part of PVA was dissolved from the structure that increases the refractive index contrast.[85] With the similar strategy, another colloidal fiber also has been prepared *via* electrospinning the aqueous mixture of P(St-MMA-AA) and PVA.[86] After preparation, directly printing H_2O ink onto the fiber surface that a confused and blur image can be formed due to the morphological transition of the colloidal fiber from the fiber aggregation to latex aggregation with the dissolution of PVA by water, while a clear and clean image is successfully printed onto colloidal fiber treated with ethanol, due to that the ethanol treating process compacts the fiber structure and lowers the spreading and wetting behavior of the ink on the fiber structure, thereby contributing to the formation of high-quality pattern.

Wet spinning is a common and efficient method widely used for fiber preparation. For wet spinning of SCF materials, the key point is the *in-situ* formation of fiber shape upon spinning process, which then supports the ordered structures assembled within it. Keep this in mind, polystyrene-divinylbenzene polydopamine (P(St-DVB)@PDA) core-shell particles dispersed in PVP aqueous solution was used as spinning solution, which was then injected into continuous outer fluid (THF) via wet spinning.[87] When the coaxial laminar flow of the two fluids merged at the exit of the inner tube, stable W/O jetting flow was formed because of the miscibility between water and THF. Since both P(St-DVB)@PDA core-shell particles and PVP were not compatible with THF, fiber-structured materials composed of core–shell particles and PVP could be *in situ* formed with the diffusion of internal water to THF in the continuous phase at the exit of the inner tube. Thereafter, with

complete water removal, amorphous colloidal array structures of P(St-DVB)@PDA core–shell particles are generated to bring green structural color for the fibers.

CLC organization within fiber

CLCs with both chiral nematic photonic assembly behavior and great processibility are leading candidates to produce self-supporting SCF materials. Nonetheless, the Plateau–Rayleigh instability effect should be considered. Lagerwall's group[26] reported a simple approach of using solvent to balance the viscoelastic properties of a CLC precursor solution, enabling continuous production of mechanically robust CLC filaments. This strategy is easy to operate and free from any extra additives disturbing the CLC chiral organization. Nonetheless, the viscoelastic property of CLC precursor is quite sensitive to solvent concentration: too little solvent makes CLC precursor too hard to form into filament shape, while excessive solvent renders CLC precursor too fluid to suppress the Plateau–Rayleigh instability. Only with solvent (*i.e.*, dichloromethane) loading at optimized 20% by mass (Figure 8A), as-diluted CLC precursor is able to allow fiber forming, *via* deposition on a rotating mandrel followed by solvent evaporation (Figure 8B). Upon preparation, CLCs align uniaxially induced by the extensional flow, which then transition to the thermodynamically stable cholesteric state with the following solvent evaporation (Figure 8C). That generates CLC elastic filaments with cholesteric organization showing dynamic structure color response to mechanical strains (Figure 8D). With the same strategy, continuous meter-long SCFs have been prepared by extrusion of concentrated aqueous solutions of chemically crosslinked hydroxypropyl cellulose (HPC) (Figure 8E),[88] which can self-assemble into cholesteric organization at a critical concentration as well as present great processibility to be formed into fiber materials. As-resulted HPC fibers show vivid structure colors (Figure 8F), and display excellent optical stability to mechanical straining, repeated drying/water impregnation, and prolonged heating at 150°C (Figure 8G).

Chiral nematic organization within fiber

Cellulose nanocrystals (CNCs) are a kind of rod-like bio-colloidal nanomaterials with capability to self-assemble into chiral nematic organization to gain structure color.[89–92] Nowadays, CNC-based photonic derivatives are widely studied, while they are common in the form of dense flat films.[93–95] Extending CNC photonic film materials into fiber materials faces great difficulty, due to the Plateau-Rayleigh instability which always leads to the breakup of CNC suspensions into droplets. To address this issue, Liu et al.[25] fabricated hierarchical liquid metacrystal (LMC) fibers *via* wet spinning by using CNCs/Na-Alg/glucose mixture as spinning solution jetted into $CaCl_2$ coagulation solution (Figure 9A). Once the mixture exits the nozzle, traction forces exerted by the Ca^{2+} ions drive the Na-Alg motion outward. The fast gelation of Na-Alg and Ca^{2+} ions forms hydrogel sheath on the surface of the ejected stream, which functions as a protective casing to afford protection against shape change and provide a stable and continuous assembly environment. At the same time, the Na-Alg shear-flow induces the transition of CNC arrangements from an aligned order into a cholesteric order. In this way, after fabrication, the resulting LMC fibers present core-sheath architectures (Figures 9B-D). Within the core that a 3D topological architecture consist of cholesteric LC configurations is evident (Figures 9E-F). Nonetheless, the fast gelation at the shell affects the assembly dynamics of CNCs, that results in LMC fibers lack of long-ranged high-ordered photonic structure. As a result, LMC fibers only show color under polarized light while still present white color under the naked eye. Additionally, with the assistance of cylindrical microtubules support and rapid UV-curing reaction, continuous and scalable production of chiral photonic filaments is achieved via wet spinning of CNC/poly(ethylene glycol) diacrylate precursors (Figure 9G).[96] The resulting filaments, driven by both shear flow and chiral self-assembly, exhibit a high degree of orientation along their central axis while preserving the nano hierarchical structure of the uniaxial nematic phase. Nonetheless, the photo-cross-linked matrix produces dynamic arrest which hampers the high-ordering assembly of CNC particles, thereby resulting in poor structure ordering of cholesteric organization with 1D filament geometry. As a result, CNC-derived photonic fibers only can show optical response observed under circular polarization, and it is still challenging to achieve CNC-based SCFs with vivid iridescence under naked eye.

CONSTRUCTION OF GRATING STRUCTURE FROM FIBERS

The contents mentioned in the preceding chapters give a comprehensive and systematic discussion on impactful SCFs constructed via bottom-up strategies. As a contrast, a top-down strategy of surface patterning which involves using micro-fabrication tools to implant nano-to-micro-scaled patterns on fiber surface, is also capable to develop SCF materials. The controlled texturing of surfaces at the micro- and nano-scales is a powerful method for tailoring how materials interact with electromagnetic waves, therefore inducing light diffraction to produce structural coloration effect. Such strategy realizes the breakthrough in integrating complex materials architectures and functionalities not only locally but also along the entire fiber length of tens of kilometers, which is particularly important for the mass production of longitudinally uniform photonic fibers up to tens of kilometers.[97,98] For example, Khudiyev et al.[23] realized the vivid coloration as well as the surface functionality for fibers via a chemical-free, environmentally friendly, and cost-effective surface patterning technique. To achieve this, firstly, sub-mm class features are generated over a cm^2 class surface area on a bulk substrate called preform (Figure 10A). Second, the preform is thermally drawn into a flexible fiber device, and such process is used to scale down the surface pattern into a flexible surface-patterned (Figure 10B). Due to the submicron-scaled patterns on surface, the fibers show distinct diffraction grating (Figure 10C). When the period of patterns becomes comparable to the visible light wavelengths, meanwhile combined with the axial and transverse fiber uniformity, that bring vivid coloration for the resulting fibers (Figure 10D). With the same strategy, Qu et al.[99] also showed the ability to pattern soft fibers to fabricate micro-structured photonic fibers. Specifically, the pattern is first imprinted on a poly(styrene*b*-(ethylene-*co*-butylene)-*b*-styrene) (SEBS) preform with a pretextured sacrificial poly(methyl methacrylate) (PMMA) plate. With removing the PMMA layer that the sub-micrometer textures are implanted onto fiber which interact with sunlight to generate diffractive effect. Therefore, as-resulted fiber shows diffractive structural color as well as mechanochromic effect due to the elastic feature of SEBS preform. To extend the application of such photonic fibers, Wang et al.[100] enabled arbitrarily designed surface patterns on entire fiber surfaces with high resolution by using the direct imprinting thermal drawing (DITD) technique. Compared with the traditional thermal fiber drawing process, DITD process introduces a pair of rollers with desired surface structures, which acted as templates could create an exactly inverted surface pattern on both sides of the drawn fiber when they are directly pressed by the patterned rollers (Figure 10D). In this way, by using non-patterned polyvinylidene fluoride (PVDF) bar as the preform, PVDF fiber with the inverted surface pattern and 2D microdot array on both sides was successfully fabricated (Figure 10E). Such high quality of the periodic surface pattern on PVDF fiber surface induces the white supercontinuum laser to split into several beams in the spatial domain and lasers with different wavelengths also separated in different diffraction angles (Figure 10F). This produces a sharp 2D diffraction pattern with "rainbow" colors (Figure 10G). This method enables the mass production and systematic collection of SCFs (Figure 10H).

HOLLOW STRUCTURE COLOR FIBER

It is very interesting that, beyond structural colored solid fiber as mentioned above, introducing hollow core into photonic band gap fibers that would generate hollow structural color fiber with new functions. To make a hollow fiber with a colloidal structure, as shown in Figure 11A, Kim et al.[101] injected a photocurable suspension of silica particles dispersed in ethoxylated trimethylolpropane triacrylate (ETPTA) into the hydrophobic polyethylene capillary. Then, an aqueous surfactant solution was forced through the capillary to drain the suspension out, meanwhile maintaining a thin film of the suspension on the inner wall of the capillary due to the hydrophobic nature of the surface. With the following UV irradiation that the film polymerizes hence generating a hollow cylindrical silica–ETPTA composite film on the inner wall of the capillary to bring structure color. Tuning the size of silica particles or increasing film layers by applying sequential suspension coatings, that could obtain hollow fibers with multiple colors (Figure 11B). Such methodology is also feasible to use the glass capillary tube to support the silica–ETPTA

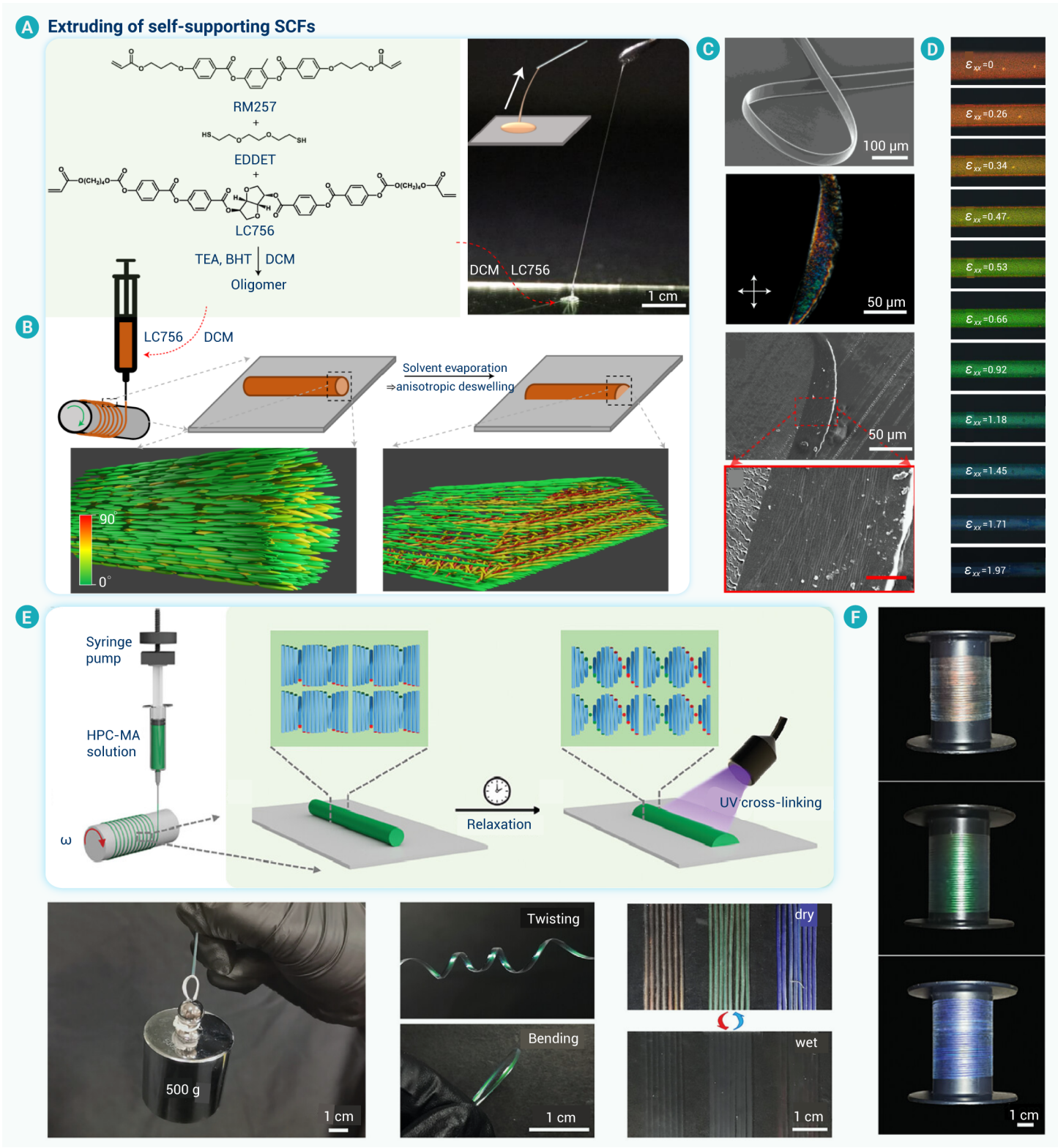


Figure 8. CLC organization within fiber (A) Extruding CLC elastomer fiber from oligomer precursor. (B) Schematics illustrating the filament extraction from a syringe containing the oligomer solution onto the rotating mandrel and the filament shape immediately after deposition and after anisotropic deswelling. (C) SEM image of as-resulted fibers (top) and their crossed-polarizer microscopy (middle) and SEM images (bottom). (D) Mechanochromic response of the resulting CLC fibers. Figures reproduced with permission.[26] Copyright 2022, Springer Nature. (E) Schematic diagram of HPC-based SCF fabrication. (F) Photographs of continuous meter-long red, green, and blue fibers. (G) The photograph of the resulting HPC-based SCFs demonstrating its load-bearing capacity, mechanical stability and wet durability. Figures reproduced with permission.[88] Copyright 2024, Wiley.

composite film coated on the inner wall followed by etching away silica particles as well as the tube template, that could produce a novel porous photonic hollow fiber with vivid reflection colors (Figures 11C-D). Another structural color microtubule fibers have been prepared from poly(dodecyl glyceryl itaconate/polyacrylamide) (PDGI/PAM) composite with using a Teflon tube and a Teflon fiber as the template.[36] As shown in Figure 11E, Specifically, PDGI precursor solution was injected into a transparent Teflon tube template, and then, a Teflon fiber was inserted into the middle of the tube. After UV polymerization followed by removing Teflon templates and finally water immersion treatment, photonic microtubule with a series of red, orange,

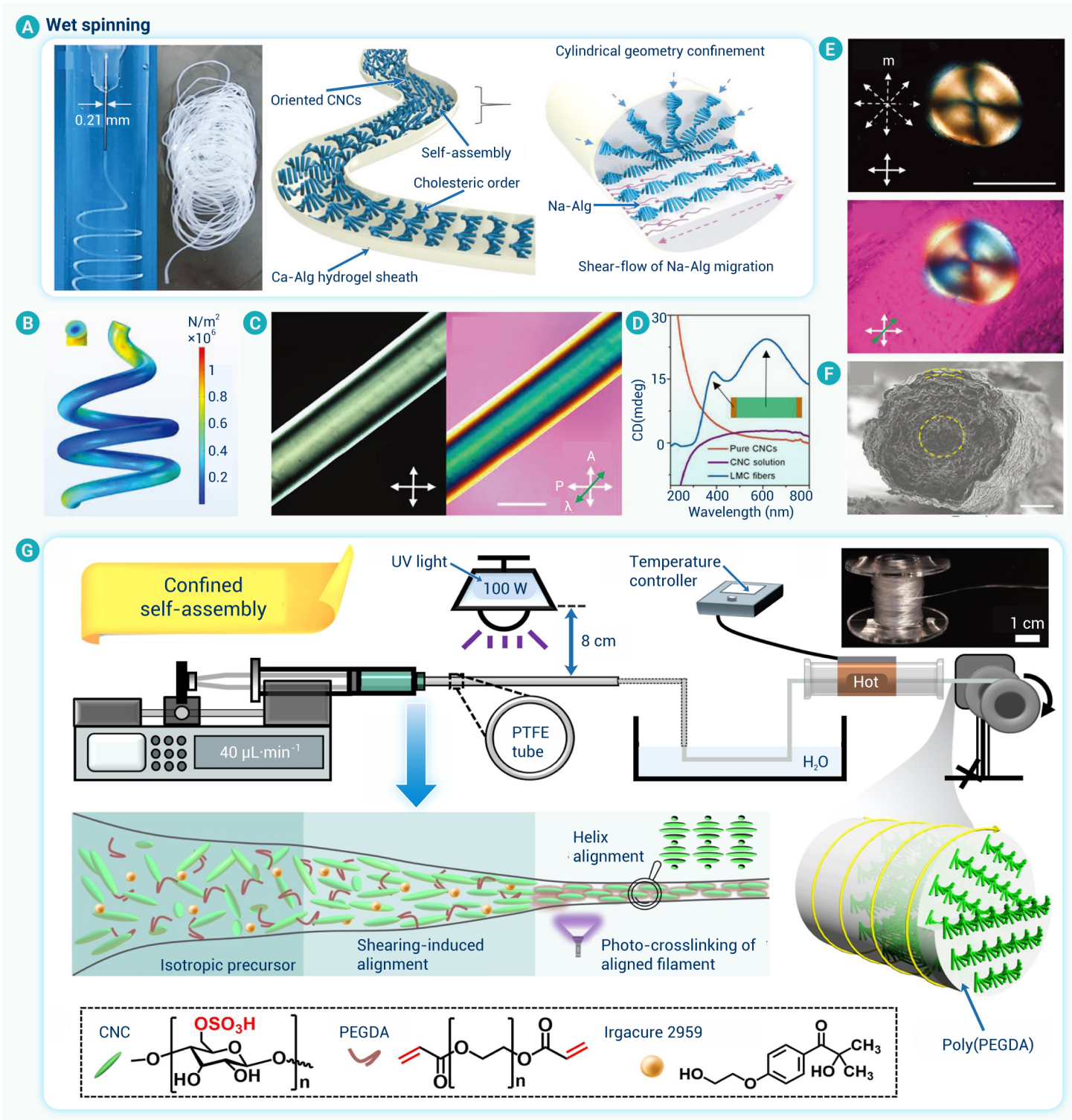


Figure 9. Chiral nematic organization within fiber (A) Fabrication of hierarchical LMC fibers *via* microchannel confinement with wet spinning strategy and the formation of the cholesteric LC phase within the LMC fibers in a generation process. (B) Simulated shear stress field distribution on the surface of LMC fibers, and the inset showing the shear stress distribution along the radial direction of LMC fibers. (C) POM image of right-tilted LMC fibers under crossed polarizers without and with a λ plate. Scale bar: 500 μm. (D) CD spectra of the LMC fibers showing the core-s structure formed. (E) POM image and (F) SEM image of the radial section of LMC fibers showing their 3D topological configurations. Scale bar: 500 μm. Figure reproduced with permission.[25] Copyright 2020, Wiley. (G) Large-scale fabrication of chiral photonic filaments with microinjection system. Figure reproduced with permission.[96] Copyright 2025, ACS.

green, and blue could be achieved by changing the size of the template (Figure 11F). Moreover, integrating the resulting PDGI photonic microtubule with piezoresistive fiber, a novel interactively full-color changeable electronic fiber strain sensor could be obtained, which enables interaction and read-out that can be visualized by human eyes. Very recently, Yang's group[102] developed a liquid crystal elastomer tube using CLC elastomers (Figure 11G). Simply, an elastomeric microchannel was filled with highly viscous CLC elastomer precursors, followed by air injection into the microchannel to form a uniform air core and shape the precursor into a sheath configuration. That makes a uniform sheath formed with enhanced cholesteric alignment before gravity and Plateau-Rayleigh instability effects (Figure 11H). Benefiting from the high molecular anisotropy of CLC in the sheath, together with the tubular geometry, as-resulted tubular structural color filament shows highly sensitive mechanochromic responses under both extension and inflation, demon-

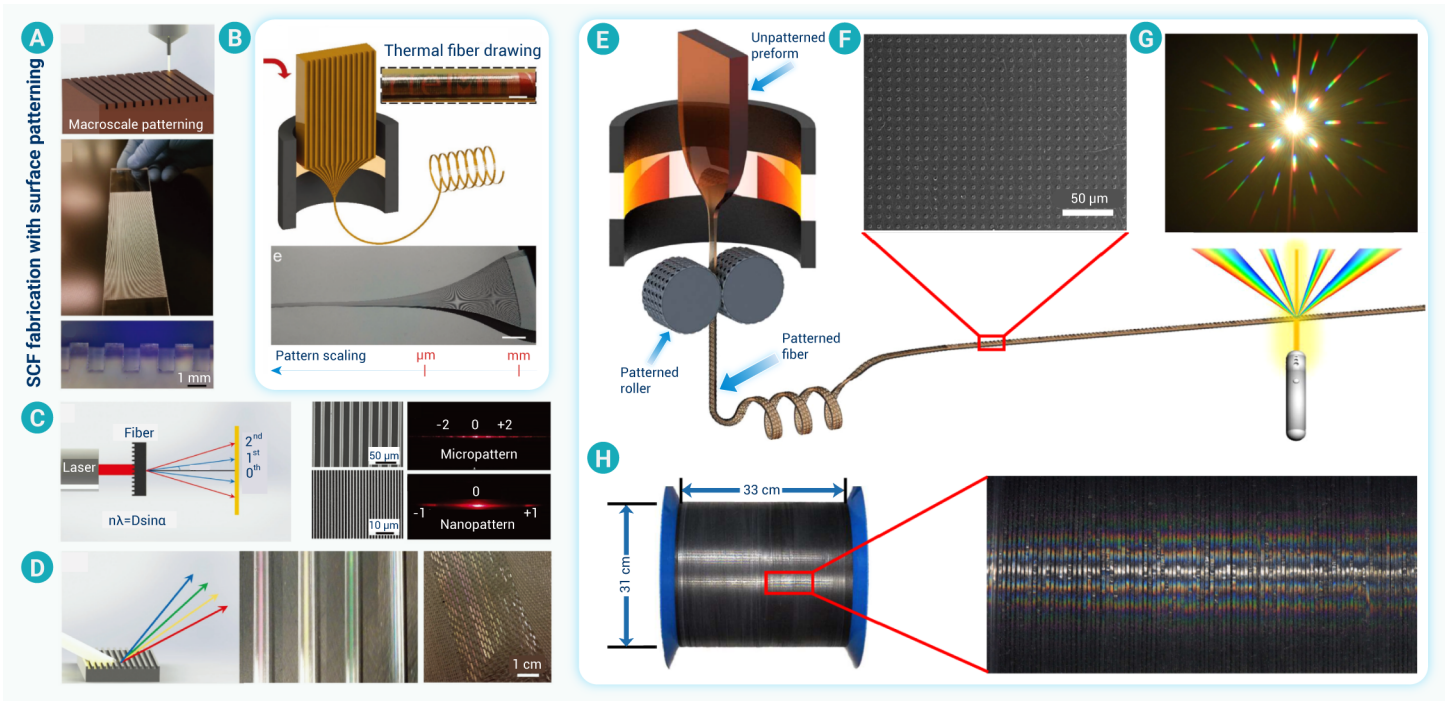


Figure 10. Construction of grating structure from fiber (A) A PMMA preform patterned by a 1 mm diameter end mill via a laser. (B) Thermal fiber drawing reduces the size of the preform as well as the surface patterns. Inset shows several meters of patterned flexible fiber rolled onto a pencil. Scale bar is 5 mm. (C) The patterned fiber surface behaves as an optical diffraction grating when the feature size is comparable with visible light wavelengths. (D) The fiber exhibits different colors when viewed from different angles and the resulting surface-patterned fibers are woven into a textile. Figures reproduced with permission.[23] Copyright 2017, Wiley. (E) Schematic representation of the preparation of a large quantity of SCFs by DITD method. (F) SEM image of 2D microdot array on fiber surface. (G) Diffraction patterns when illuminated by a white supercontinuum laser. (H) 300-meter-long fully patterned fiber collected on a cylindrical bobbin. Figures reproduced with permission.[100] Copyright 2020, Springer Nature.

strating great potential in the applications of reconfigurable alphabet displays and curvature dependent 3D photonic skins.

CONCLUSION AND OUTLOOK

Bio-inspired SCFs, which integrate the photonic effects of naturally occurring structural colors with the morphological versatility of fiber materials, represent a novel class of functional fiber materials. Featuring dye-free and pigment-free chromatic characteristics and emerging advanced functionalities, SCFs exhibit remarkable application potential in numerous high-tech and frontier fields. The key to fabricating high-performance SCFs lies in the rational construction of nano- and microscale photonic structures within macroscopic one-dimensional fiber geometries. To date, both bottom-up and top-down fabrication strategies have been developed to introduce light-responsive micro/nanostructures onto, within, or from fiber substrates, thereby producing SCFs with diverse architectures and tailorable optical performances.

Unlike conventional coloration using chemical dyes or pigments, SCFs generate vivid and dynamic colors through physical optical interactions including light interference, diffraction, and scattering within ordered micro/nanostructures. Accordingly, they possess intrinsic advantages such as high resistance to fading, environmental friendliness, unique iridescent effects, and stimuli-responsive color tunability. As a revolutionary alternative to traditional textile dyeing technologies, SCFs show great promise for eco-friendly high-performance textiles and sustainable fashion. In particular, SCFs capable of converting external physical and chemical stimuli directly into visible color changes—without relying on electronic components—are highly attractive for applications in smart wearable devices and visual sensors. Furthermore, owing to their distinctive optical characteristics including angle-dependent iridescence, polarization sensitivity, and programmable microscale patterns, SCFs can be engineered for multi-level optical anti-counterfeiting and information encryption. In addition, mechanically tunable SCFs based on cholesteric liquid crystal structures enable real-time color adaptation under mechanical tension. When integrated with computer vision systems, such fibers can achieve autonomous color matching for adaptive camouflage textiles, flexible biomimetic robots, and intelligent concealment materials. Moreover, SCFs can act as flexible optical waveguides, display pixels in woven electronic textiles, and photonic building blocks for soft photonic circuits, thereby supporting the development of fabric-based flexible displays, wearable optical communication devices, and textile-integrated photonic systems.

Although significant progress has been achieved in the laboratory preparation of SCFs using approaches including photonic crystal assembly, colloidal self-assembly, electrospinning, microfluidics, and biomimetic manufacturing, their large-scale industrialization still faces critical constraints. The primary bottleneck is insufficient structural stability and color fastness. In most SCFs, structural colors rely on colloidal photonic crystals assembled through weak physical interactions such as hydrogen bonding and van der Waals forces. These ordered nanostructures are vulnerable to destruction under mechanical stretching, friction, laundering, high temperatures, and solvent exposure, resulting in color fading or even complete loss of structural color. Second, the continuous and high-speed manufacturing of high-quality SCFs remains extremely challenging. Current fabrication methods are mostly limited to laboratory scales and cannot simultaneously satisfy the requirements of long-range ordered nanostructure assembly and high-rate processing, making it difficult to produce kilometer-scale uniform SCFs with consistent optical performance. Third, the introduction of highly ordered periodic nanostructures often compromises the mechanical properties of fibers, including tensile strength, flexibility, and abrasion resistance. Densely packed nanoparticle assemblies tend to cause brittleness and cracking under repeated deformation. Meanwhile, crosslinking modifications intended to enhance structural stability often disturb the photonic bandgap and degrade the original structural color. Therefore, balancing mechanical robustness, washing durability, and tunable optical performance remains a major challenge in materials design. Finally, precise color modulation and multicolor patterning—although essential for practical applications—are difficult to realize. Accurate control over nanoparticle size, interlayer spacing, and structural orientation to achieve full-spectrum non-iridescent colors remains technically complicated. In addition, existing assembly techniques struggle to achieve mass customization of multicolor patterns on single fibers or woven fabrics. Furthermore, the response speed, reversibility, and stability of dynamic stimuli-

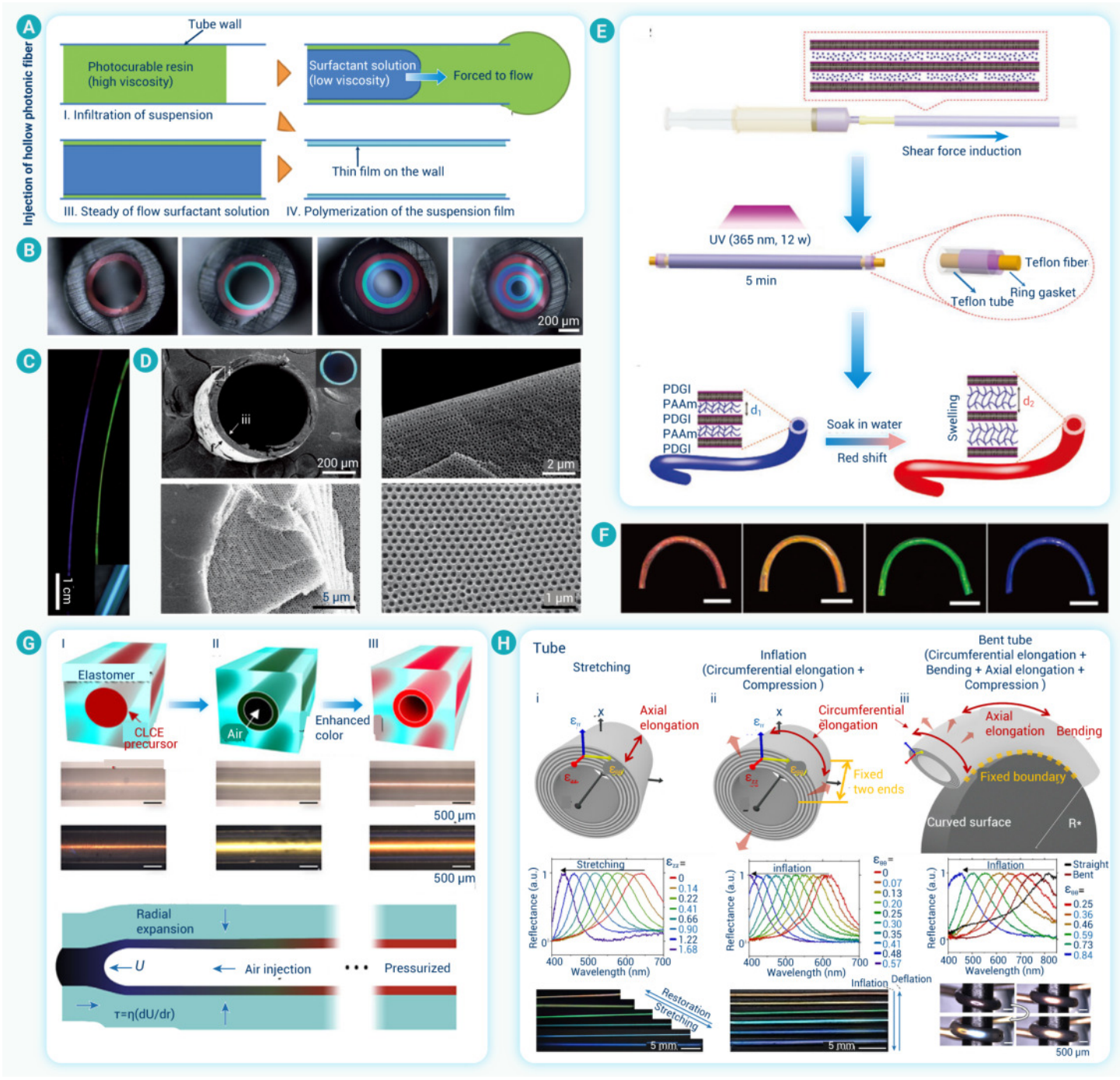


Figure 11. Construction of hollow structural color fiber (A) Schematic illustration of the coating process in tube wall using the photocurable resin. (B) Sequential coating of up to six layers. (C) Porous photonic crystal fibers colored green and violet. (D) SEM images of a porous photonic fiber: cross-sections, a fractured outer surface, and an inner surface. Figures reproduced with permission.[101] Copyright 2012, Wiley. (E) Schematic illustration of the fabrication process of PDGI photonic crystal hydrogel microtubule. (F) Optical images of PDGI microtubule. Scale bar: 1 cm. Figures reproduced with permission.[36] Copyright 2020, Wiley. (G) Schematic illustration of the fabrication of liquid crystal elastomer tube. (H) Schematic diagrams of liquid crystal elastomer tube under stretching, inflation, and bent tube inflation and reflectance spectra and the corresponding photos of the liquid crystal elastomer tube under deformations of stretching, inflation, and bent. Figures reproduced with permission.[102] Copyright 2025, Wiley.

responsive SCFs under external triggers such as temperature, pH, strain, and humidity still require substantial improvement.

Given the above challenges, future research and development of SCFs will focus on scalable manufacturing, high structural stability, multifunctional integration, and intelligent responsiveness. Technically, there is an urgent need to develop integrated in-situ spinning strategies that combine nanostructure self-assembly with continuous fiber extrusion to enable industrial-scale, high-throughput production of long SCFs. Structurally, advanced material design concepts including core–shell configurations, composite photonic layers, and melanin-inspired light-absorbing components will be adopted to enhance color saturation, laundering durability, abrasion resistance, and thermal stability. Functionally, stimuli-responsive SCFs will be further developed for smart textiles, visual sensing, flexible displays, and information encryption, expanding their applications beyond conventional coloration toward next-generation intelligent and interactive textile systems.

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AUTHOR CONTRIBUTIONS

Yuanhan Tang: Data Curation, Formal Analysis, Investigation, Writing–Original Draft. Haixing Jiao: Resources, and Software. Baiqi Song: Investigation, and Validation. Weilin Xu: Validation, and Supervision. Xiaofang Zhang: Conceptualization, Supervision, Writing–Review & Editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

No new data were created or analyzed in this study.